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Integrated waste management system and new business pattern: strategies and modelling towards Circular Economy

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Politecnico
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Department of Mechanics, Mathematics and Management

Mechanical And Management Engineering Ph.D. Program

SSD: ING-IND/17–Impianti Industriali Meccanici

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Course n°30, 01/11/2014-31/10/2017

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INTRODUCTION

Nowadays, one of the biggest challenges is decoupling economic growth from the environmental impacts related to resource depletion, pollutants emissions and waste management. It represents an ambitious goal for both the extent of required changes and the breadth of its scope since it requires not only to focus on the priorities of the current economic recovery and growth, but doing this by creating an economy based on an efficient use of resources, on low-carbon emissions and on climate resilience future.

It is now a requirement, which can also be defined as *urgency*, dictated by models that for a long time have considered the environmental aspects as *side-effects* subordinated to the achievement of economic results. The linear economic model is the result of this culture.

Up to now, the economic model *'take, make, dispose'* has been pursued to ensure population needs. It has contributed to human development and prosperity, optimizing the elements independently, and not taking into account environmental impacts on the planet.

The linear model is based on the use virgin raw materials as inputs for its production processes (*take*) and on the conversion of these inputs in products (*make*) destined to consumption. Wastes generated by production processes are disposed of, as well as products at the end of their lifetime (*dispose*). It is a model that is reaching its physical limits as some evidences proved.

Two are the most important phenomena that need to be jointly assessed: the steady rise of the world's population at a yearly rate of 1.18 %, as well as the increase in per capita resource consumption in developing countries for which are registered values almost equal to those of the developed ones (Monticelli, 2016). The unsustainability of this model depends on the scarcity of the resources it draws on and on his considerable environmental impact. The higher the resource consumption, the higher the amount of virgin raw material extracted and wastes landfilled. On one side, the elevated consumption of natural resources causes huge damage to ecosystems, in terms of global climate change, landscape degradation, and loss of biodiversity. On the other side, landfills are recognized as the main contributor for methane gas emissions (greenhouse gases as methane are recognized the main responsible of the climate change), and contaminants in air, water, and soil. It is therefore necessary to explore new growth opportunities that will meet the needs of a larger and more demanding population, but with a concurrent and equally important environmental impacts focus that, if left undressed, will further undermine the possibility of reaching development (Fraccascia, 2016). The negative effects due to the linear business model in threating environment and ecosystem are widely recognized and faced in literature (European Commission, 2014; Mazzantini, 2014; Park and Chertow, 2014).

In this context, increasing attention is being given from both academics and businesses to the circular economy (CE) paradigm which has been defined as a way to decouple economic growth and environmental burden (Sauvé et al., 2015). The Ellen MacArthur Foundation, Mckinsey and SUN have identified that through circular economy implementation Europe can take advantage of the impending technology revolution, generating economic opportunities, creating new job and counteracting GHGs emissions. The areas of intervention are manifold and with a high potential.

Circular economy fosters a general rethinking of the traditional linear model and orientates the choice to more effective business models, able to jointly 'adding/extracting' value from existing assets. As stated by the

European Commision: “[…] Circular Economy looks at products and waste […]”.

On one side, adding value is possible through an infinitely replicable sequence consisting in redesign of production process and products– sale either of product or of its use- pick back – refurbishment – sale- pick back and so on. Several business models have been identified as enabler factors in this direction.

On the other side, extracting value is possible through a right management of waste consisting in recycling practices and consequently material and energy recovery. Waste minimization and prevention along with preparation to reuse pursued by the former and recycling and energy recovery pursued by the latter, are completely in compliance with pillars of waste framework directive.

However, in both case the implementation is not fully exploited in the huge potential. Hence, the adoption of business model ‘circular-oriented’ struggle to take hold. The causes may lie in the lack of assessment of the barriers perceived by the various actors involved in such a change and of effective impacts on different sustainable performance.

Being a new business model, it is probably ‘*not mature enough to be born spontaneously*’. Both long-term sustainability and support policies should be evaluated.

On waste management side, although the progress so far achieved, a considerable amount is still landfilled and too little recycled (EU, 2017). Adverse effects on climate change is considerable. The Intergovernmental Panel on Climate Change identifies the waste sector as a key sector to counteract GHGs emissions. Therefore, not addressed environmental problems caused by a not efficient waste management could undermine the challenge posed the 2015 Paris Climate Change to cut emissions of more than 90% and to keep global warming below 2°C. Not deserving attention has been paid on such an issue. As stated by European Union, the lack of a focus on the close link between resource use, recycling, recovery and environmental impacts forces policymakers to base policies on poor proxies of environmental impacts rather than on well-established knowledge (European Union, [EN], 2006).

This thesis is devoted to address both the unexplored theme in an overarching perspective. Elicitations due to the implementation of the abovementioned business pattern jointly on supply chain level and single actor are addressed. Effects on systems performance are formalized. Potential policy driver to ensure sustainable viability are identified too.

To overcome the inner complexity characterizing waste management, its decision making process is mapped into a five-level decision framework able to catch closed link among decision variables and environmental impacts. The potential of such a sector in tackling GHGs emissions is faced by developing an optimization model that ensure the operative and strategic planning with lowest level of CO_{2eq} emitted. Solid waste management system has a multi-dimensional nature. The effectiveness of such a system depends not only on technical and organizational issues but also on socio-cultural factors like citizens' cooperation, education and participation in awareness campaigns. Indeed, an analysis of how a better participation affects performance is carried out by a definition of an 'ad-hoc' index in a scenarios analysis. Thinking about how this systematic knowledge can become easily accessible, features owned by a user friendly decision support system are investigated resulting in an Artificial Neural Network that predicts direct and avoided emissions along with financial flows and collection arrangements. 'Circularity' at city level rests, as emerging startegies, on "smartness". Although the steady progress already experienced, greater efforts can be done to involve 'smart actors' who cooperate in decision-making on public or social services. This efforts routes to the development of a smart tool, namely a planning and a communication/information tool to establish one of the most powerful index in the environmental context, that is the carbon footprint.

The thesis is organized as follows. Chapter 1 discusses the general framing about circular economy principles and waste management. Through a critical review of the literature, research gaps are identified. Consistently, the specific research questions and related research objectives are presented. A logical scheme of research questions, objectives and the links among them is shown too. Chapter 2 addresses a specific business models supporting the transition towards CE and its impact on supply chain level. Chapter 3 faces the development of a holistic framework in integrated waste management. A Mixed Integer non Linear Programming Model to minimize environmental impact of waste management is developed in Chapter 4. The role of human participation in system performance is addressed in the same chapter. The development of 'support-tools' for different stakeholders and aims is the theme of the last two chapters. In particular, in Chapter 5 an ANN-based decision support is presented. A web-app for carbon footprint evaluation is addressed in Chapter 6. Finally, conclusions are provided.

CHAPTER 1

CIRCULAR ECONOMY AND WASTE MANAGEMENT: GENERAL FRAMING

1.1 Circular Economy principles

Recently, the concept of "Circular Economy" has been widespread and has acquired a significant boost. It should be pointed out that there is not a shared and unique definition of circular economy and it is not easy to orient among other similar concepts that present both points in common and some real overlaps (Bigi, 2016), among which Sustainable Development, Green Economy, Life Cycle Thinking, Industrial Ecology, Extended Producer Responsibility .

Among the most accredit definitions, there are the following one:

“ [...] *The circular economy is an economic production and exchange system that, along all the stages of the product life cycle, aims to increase the efficiency of resource utilization and decrease the environmental impact while developing the well-being of people* [...]*”* (ADEME — Changement climatique)

“ [...] *a circular economy implies reducing waste to a minimum as well as re-using, repairing, refurbishing and recycling existing materials and products. What used to be considered as 'waste' can be turned into a valuable resource* [...]*”* (European Parliament)

[...] "An economy that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles [...]" (Ellen MacArthur Foundation, 2013).

According to (Ellen MacArthur Foundation, 2013), the main pillars on which that economy is based are:

- *"Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows"* entailing that technology and processes are chosen wisely basing on their use of renewable or better-performing resources.
- "*Optimize resource yields by circulating products, components and materials at the highest utility at all times in both technical and biological cycles";* meaning designing for remanufacturing, refurbishing and recycling to keep technical components and materials circulating in the economy, preserving embedded energy and other value.
- *"Foster system effectiveness by revealing and designing out negative externalities"* this includes reducing negative impact managing externalities, such as land use, air, water and noise pollution, release of toxic substances and climate change.

CE represents a 'win-win' strategy for companies and users since opportunities are different and equally shared among them. From the companies' point of view, opportunities rely on increased profit, greater security in supply, new demand for business service and improved customer interaction and loyalty. On the other hand, for the user point of view, opportunities relates on both lower prices and cost of ownership and increased utility due to a wider choice.

In Figure 1, it is shown the holistic framework and relative phases on which Circular Economy is based.

As the European Commission (Maurer, 2016) states, "Circular Economy looks at product and waste". It looks at product through the implementation of business model operating from the early phase of designing to the final phase of use and dismantling. As well as, it works on wastes since, with the right approach and technologies, many waste streams become an important income stream (Mckinsey, 2016). This is a landmark change whereas for a long time wastes were conceived and treated in a 'zero added value' pattern.

Figure 1- Holistic Circular Economy Framework (re-elaborated version of European Commissions)

1.1.1 Circular Economy business models

To enable the transition towards CE paradigm, five business model are recognized in literature as the most suitable (Accenture, 2014). In (Ellen MacArthur Foundation, 2013) a classification of these models is provided considering the different production phase on which they act. The business models - described below - can be jointly or separately applied to help companies achieving a greater and more efficient resource productivity and at the same time ensuring customer value and reducing environmental impact.

- *Circular Supply Chain:* it means provide renewable energy and biological or fully recyclable inputs to replace limited lifecycle resources.
- *Resource Recovery*: it means to guarantee recovery value embedded in a product at the end of his life cycle. Having its roots in traditional recycling processes, this business model leverages new technologies and capabilities to recover almost any type of resource output at a level of value equivalent to, or even above, that of the initial investment. Industrial symbiosis is the most representative example in that field.
- *Product Life Extension:* by repairing, upgrading, remanufacturing or refurbishment, residual values is preserved or even improved rather than lost through waste. In this way, products remain economically useful for a longer time and product upgrades are more targeted (for example, an obsolete component is replaced instead of the entire product).
- *Sharing platform:* it means promoting sharing platform aiming at facilitate the sharing of overcapacity or underutilization, increasing productivity and user value creation among product users, and individuals or organizations.
- *Product as Service:* it replaces the traditional 'buy and own' model. Instead of the product, the service for the product use is sold through leasing or pay-for-use arrangement. This model aims at boosting product durability and upgradability upside down, shifting incentives from volume to performance. With a Product as a Service business model, product longevity, reusability, and sharing are no longer seen as cannibalization risks, but instead, drivers of revenues and reduced costs.

Fundamentally, unlike linear systems, CE models are based on resource conservation and material flows valorisation through reuse, recovery and recycling.

1.2 Waste management as key driver towards ‘circularity’

For centuries, waste management has been simply conceived a way to get rid of the waste materials by landfilling or incinerating in the most cheap way possible (Ghisellini et al., 2015; Wilts et al., 2016). Unfortunately, this is still a dominant disposal pattern causing jointly a consistent loss of valuable resources and huge environmental impacts. Recently, this approach is increasingly being disputed because the idea of a circular economy has attracted growing attention in the public and social debate.

In this perspective, the waste management industry will become a key sub-sector in the transition towards Circular Economy.

The efforts required to turn waste from the traditional 'no-value' stream with negative economics externalities to a ‘high added value’ resource are significant. It demands for a wholesale transformation of the waste management sector to a secondary resource recovery sector and its integration with a manufacturing sector which continues to rely on virgin resources (Gregson, Nicky; Crang, Mike;Fuller, Sara; Holmes, 2015).

In Europe, leading to a circular economy from wastes is a three-fold challenge. Firstly, it requires identifying the appropriate treatment and valorisation technologies for each type of waste ensuring the recovery of both physical and economic value so that waste become goods marketable. Secondly, a demand for secondary raw materials on large-scale should be ensured since the lack of market request would made the upstream technological effort useless. Lastly, but not less important, strategies pursued should take into account the problem of environmental impact of waste management, until now neglected.

In this sector, legislation and relative guidelines are complex and constantly updated. The Waste Framework Directive (European Commissions, 2008) sets the overarching legislative framework. It explains waste management core concepts, including the 'polluter pays principle' (ensuring that the costs of preventing, controlling and cleaning up pollution are reflected in the cost of goods) and the 'Waste Hierarchy'.

As a forerunner of circular principles, the Waste Hierarchy establishes a priority order for managing waste flows. The principle is to encourage the options that deliver the best overall environmental outcome. Consistently, waste prevention represents the priority strategy. Afterwards, it is envisaged the recovery for reuse, followed by recycling. Energy recovery (electricity or heat) through 'waste to energy' practices is less favoured than recycling, but better than landfill that is the least favoured option.

In 2015, the European Commission adopted a package on the circular economy, which includes both an action plan and legislative proposals on waste. The latter concern long-term recycling targets for urban and packaging waste, measures to promote greater use of economic tools (dump fees), general requirements for producer's extensive responsibility. Although the progress so far obtained, over a quarter of municipal waste is still landfilled and less than half is recycled or composted, with wide variations between Member States (European Parliament, 2017).

On Tuesday 14 March 2017, the European Parliament adopted the "waste package", including a series of resolutions designed to favour recycling and re-use of waste, limit landfilling, and reduce food waste. This is a step forward in the promotion of a circular economy. It follows the adoption of the Circular Economy Action Plan by the European Commission and the relevant public consultation (Arpae, 2017).

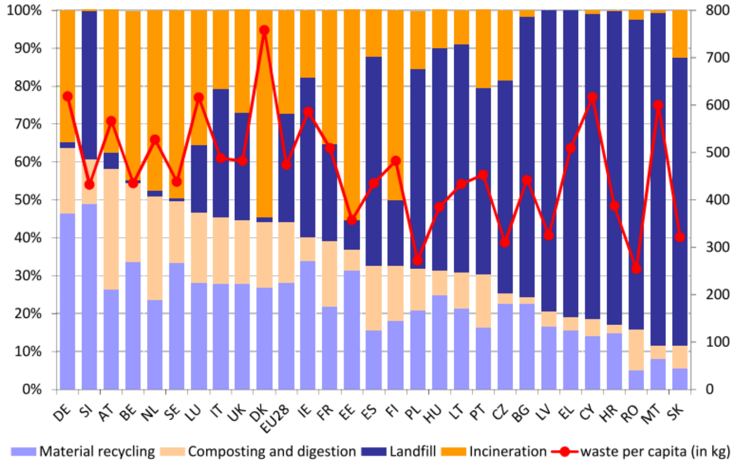


Figure 2- Waste treatments and per-capita production in EU-28 (European parliament, 2017)

1.3 Research questions and objectives

The aims of the thesis encompass the implementation of both new business pattern and efficient integrated waste management to foster CE transition. In the following, that *macro*-objective will be detailed by defining specific objectives that respond to the research questions addressed during the PhD course. The identification of the research questions has started from an in-depth analysis of both scientific literature and strategic/policy instruments of the reference context.

Circular economy mainly emerged in literature through three main action, i.e the so called 3R's Principles: Reduction, Reuse, Recycle (Feng et al., 2013; Ghisellini et al., 2015; Sakai et al., 2011). Business model innovation has been widely recognized as one of the levers that can effectively support a transition towards the CE (EEA, 2016; Elia et al., 2016a; Ellen MacArthur Foundation, 2013).

(Schulte, 2013) identifies five key principles on which a circular business model should be based: waste minimization, understanding the total ecosystem of the business, maximizing flexibility through design, use of renewable energies and energy efficiency maximization.

Some insights are present in literature about specific sectors. (Despeisse et al., 2016) analyze the potential of 3D-printing to open CE paths, reviewing some of the main research questions on the topic, including considerations on the business model transformation. (Johansson et al., 2016) give an example of business model conceptualization towards CE, exploring the main issue to address when designing a PSS for urban mining. Moreover, an analysis of business model innovation towards CE has been presented by (Weissbrod and Bocken, 2016), who started from the test case of a clothing retailer to understand how a company can build the necessary organizational capabilities to move from linear to circular model, summarizing their findings through nine key lessons.

On a more strategic level, (De los Rios and Charnley, 2016) focus on the transformation that CE requires for production and consumption systems, identifying the role of design as a key to tackle this challenge. Starting from some multinational enterprises case studies, they try to identify the main requirements and proficiencies necessary for successful design innovations. It has been estimated that quite the 80% of the environmental impact of a dismantled product is influenced by the design phase (The Guardian, 2014).

(Cohen and Muñoz, 2016) investigate the implementation of Sustainable Production and Consumption (SPC) systems and sharing economy initiatives in cities, elaborating a typology of sharing SPC-oriented activities. On one side, the authors underline the potential of SPC and sharing economy for positive implication on sustainability and Circular Economy, on the other side, they point out the lack of empirical evidence to evaluate the actual impacts of these paradigms. Similarly, (Witjes and Lozano, 2016) propose a collaborative framework between sustainable public procurement and sustainable business models oriented to the transition to CE. The concept of upgradability as a way to contrast product obsolescence, combining it with the PSS business model is investigated in (Pialot et al., 2017). The result is a hybrid model called "Upgradable PSS", in which optimized maintenance, refurbishment and offer servitization can open new perspectives for both businesses and customers, who would act in a continuous interaction, and facilitate the transition to a CE. The authors underline how the advantages of such an offer could push the customer to choose use-based models rather than ownership-based ones, helping the business to increase control over products and components flows.

Despite the implementation of new business models has been identified as an enabling factor for the transition to CE, a few studies have attempted to analyze the challenges related to business innovation oriented to circularity and its effective impacts on a supply chain level identifying all the actors involved. A fortiori, it relates combinations or hybrid business models.

Moreover, researches including the jointly economic, environmental and social advantages for companies and customers is still lacking, as well as assessment tools to verify the effectiveness of circular strategies although it is necessary for a successful implementation.

Starting from this premises, it is evident that the path towards the implementation of a CE is still long (Elia et al., 2016a; Ellen MacArthur Foundation, 2013). Business models based on refurbishment and product life extension have been already tested in the electronic and electric equipment (EEE) sector (Ellen MacArthur Foundation, 2013; Moreno et al., 2014), which is crucial both for the volume of e-waste generated annually (Eurostat, 2016) and for the composition of end-of-life products, which contain high value materials, as well as hazardous substances (Elia and Gnoni, 2015). The Circular Economy Package (European Parliament, 2017) strengthens the interest in this sector since the electrical and electronic waste -common defined 'e-waste' - is one of the fastest growing flow with a steady yearly increase of 3-5%.

Specifically, (Moreno et al., 2014) present two case studies of circular-oriented PSS applied in the large household appliances sector, displaying the results of a workshop aiming at identifying the main barriers, drivers and benefits related. Despite the high value of end of life materials from e-waste and the critical importance of this flow, studies about business model innovation oriented to circularity are still in early stage.

Consistently with the research gaps just outlined, the following researches questions are addressed:

RQ1: *What are the main impacts and relationship that CE oriented business model would elicit on the three main dimensions of sustainability at both supply chain level and single actor? What are the changes required in supply chain?*

RQ2: *What are the potential policy drivers to foster the transition? And what their implication on system performance?*

Coherently, the following research objective (RO) is pursued:

RO1: *Development of a Fuzzy Cognitive Map to:*

- *Identify main change on supply chain level*
- *Quantify direct and indirect effects due to the adoption of a new business model (based on PSS and closed loop) on both supply chain level and single actor involved.*
- *Identify supportive policy measures to foster the transition ensuring economic viability for companies and users.*

All in all, the challenge ahead towards circular economy does not stop here calling for an innovative and more sustainable integrated waste management.

The Intergovernmental Panel on Climate Change (IPCC) identifies the waste sector as one of the seven sectors that contribute to the increased atmospheric concentration of GHGs. Concerns about emissions are increasing and require ever larger scale actions. The 2015 Paris Climate Conference is a milestone for the strengthening of a global action toward a low-carbon society and a climate-resilient future. The Intended Determined National Contribution protocol, signed by 185 States, pursues to cut emissions of more than 90% and to keep global warming below 2°C. To this purpose, the European Council states that global emissions of greenhouse gases (GHGs) should be stabilised within 2020, reduced by 2050 of at least 50% compared to 1990 and close to zero by 2100. A wide literature is available on methods and experience to tackle urban GHGs emissions(Blackhurst et al., 2011; Hoornweg et al., 2011). The United Nations Environmental Program (United Nation Environment Program (UNEP), 2010) recognizes waste management as having a strategic role in emissions' reduction.

Although the progress so far, there is still a plenty of room for improvements to mitigate GHGs emissions through better waste management (European Environment Agency, 2011) by stimulating innovation in recycling, limiting the waste landfilled, and creating a virtuous model to change consumption patterns (EUROPEAN COMMISSION, 2015).

Waste management is a really complex process due to the high number of decision variables and relationships involved (Soltani et al., 2015). Moreover, the effectiveness of a waste management system depends on the degree of integration and awareness of all actors involved: users, service providers, local authorities, and policy makers. Designing in an integrated perspective a waste management system, requires both experiential and theoretical knowledge. Indeed, technical, economic and environmental performances are obtained after basic organizational choices are taken. Public actors are not always aware nor of solutions adopted or the way they have been found.

Waste management covers a large research field as it is witnessed by the wide available literature. The selection of the most appropriate model should be based on the scope of the evaluation (Karmperis et al., 2013). An interesting model classification is proposed in (Pires et al., 2011) where models are grouped into two categories: systems engineering models and system assessment tools. System engineering models are mainly used to select technologies, compare management options and facilities siting while system assessment tools focus on existing waste management systems which are investigated by scenario analysis. Such models can be adopted to focus on specific problems or in a broader view to integrated system. Specific problems may relate all the different stages of waste management system from collection to treatment and valorisation processes. Waste collection provides a significant contribution on total pollution and management due to the high level of fuel consumption and the labour-intensive (Johansson, 2006; Tavares et al., 2009). Consistently, waste collection models gained even more attention over the years. In (Nguyen-Trong et al., 2017), an economic oriented model to minimize waste collection costs is proposed integrating a Mixed Integer Linear programming model with an Agent-based model and GIS analysis. In (Anghinolfi et al., 2013), a dynamic model integrated in a GIS-based system optimize the transportation costs and the benefits from materials recycled sales. Similarly, the selection of the best treatment strategy is center of intense debate in literature and in practice. An efficient waste treatment strategy should be cost-effective and environmental friendly for all different actors involved in (Soltani et al., 2016). In (Mummolo, 1995) a municipal landfill site selection problem is formulated and solved by an analytic hierarchy model. An adaptive neural fuzzy inference system has been implemented in (Younes et al., 2016) to predict the solid waste generation and determining the required land for waste disposal and the capacity of the proposed landfill. In (Soltani et al., 2016), a game theory approach is used to select sustainable waste to energy technologies for RDF in Metro Vancouver allowing fair shares of costs and benefits among different stakeholders . Both advantages/disadvantages and critical factors of the different methods for waste treatments are clearly analyzed in (Finnveden et al., 2005) in LCA perspective. Focusing on specific problem means face either strategic or operational problems. The planning horizon and related models depend on whether strategic or operational objects are pursued (Gnoni et al., 2008). Strategic decisions problems like localization, technologies' selection for waste treatment and valorization are strategic choices taken at regional level. Operational decisions problems like collection service design, vehicle routing optimization are operational choices taken at municipal level. Strategic and operational problems affect each other.

However, both scientific investigations and real cases are carried out separately, and it seems that they lacked the viewpoint of the entire waste management system. Just one optimized treatment process might have a negative effect on the entire system (Tabata et al., 2011). Thinking to the integrated system is the only solution to ensure sustainable performance optimality . Integrated solid waste management systems mean combining waste flows, collection, treatment and disposal technologies to reduce the environmental and social impact at an acceptable cost for the community (White et al., 2001). A system dynamic model is adopted in (Sukholthaman and Sharp, 2016) to investigate the impact of waste collection and transportation on the effectiveness of waste management system performance. Results show how the amount of recycled waste, the amount of waste landfilled and relative costs occurred greatly varies with different level of source separation. Consistently, multiple strategies to encourage residents in source separation are highlighted too. In(Lee et al., 2016) a mixed integer linear model is developed to provide decision makers with a tool to minimize waste management cost. Useful information such as the number of trips made from collection points to landfill or to incinerator, the amount of waste landfilled or burned can be obtained from the model. The 'LCA-IWM Assessment Tool', detailed in (den Boer et al., 2007), allows modelling waste management scenarios to assess sustainability performance at municipal level. The framework is complex and considers three subsystems: temporary storage, collection and transport and treatment, disposal and recycling.

Economic issues are widely investigated in an integrated perspective. Although recent studies indicated that municipal solid waste has been an important contributor to greenhouse gas (GHG) emissions (Lu et al., 2008; US EPA, 2008) waste management decisions are often made locally without concurrent quantification of GHG mitigation actions. Indeed, the importance of the waste sector for reducing global GHG emissions has been underestimated over the years (Bogner et al., 2007). Indeed, most of the models to optimize solid waste management processes overlooked global warming potential (GWP) impacts. Few attempts in that direction can be found. (Chang, N.B, Qi, C., Islam, K., Hossain, 2012) investigate GWP impacts through cost–benefit criteria to carry out optimal planning of a typical waste management system in Pennsylvania. Results highlight the importance of recycling processes in tackling GHG emissions.

Consistently, investments to improve the collection and separation of recycled materials are needed. Although the priority of less waste production and less waste disposed, additional emissions benefits can arise from the production of electricity through CH_4 in landfill site. (He et al., 2011) presented two mixed integer bi-level decision-making models for integrated municipal solid waste management and GHG emissions control. The bi-level decision making model sequentially optimizes at the top level (i.e. national level) the GHG emissions, and the down level (i.e. municipal level) the total management cost. Results are the identification of allocation schemes for waste flows, the sizing, and the siting for facility, and the evaluation of the minimized total management cost and GHG emissions for a defined planning horizon. The model does not consider emissions from collection. As stated by the authors, the inclusion of that contribution can lead to emissions savings even more highs.

Consistently with the research gaps just outlined, the following researches questions are addressed:

RQ3: *How can the decision making process be mapped to design waste management system in integrated perspective? What are both strategic and operational choices?*

RQ4: *How can the integrated waste management potential be exploited to tackle GHGs emissions? What are the variables on which act? And what the effects?*

Coherently, the following research objective are pursued:

RO2: *Definition of a multilevel decision framework for both strategic and operational planning of the integrated waste management system.*

RO3: *Development a mixed integer non-linear programming model to minimize the GHGs emissions of the integrated waste management system.*

Solid waste management system has a multi-dimensional nature. The effectiveness of such a system depends not only on technical and organizational issues. Aspects and enabling factors that affect waste management performance are explicitly reported in (Guerrero et al,2013).

The analysis shows that an effective system also depends on socio-cultural factors like citizens' participation and cooperation, education and awareness campaigns. The consumer is responsible and primary actor for the proper separate collection of waste. His will to implement a conscious and correct collection represents the beginning of the circularity.

Indeed, one of the most important progresses is increasing the level of awareness among different actors that affect waste management systems' performance. Understanding behaviour influences would be useful to design a set of targeted intervention improving this pivotal dimensions thus amplifying effects of technologies/organizational improvements.

RQ5: *What are the effects of citizen' greater participation on system performance?*

Coherently, the following research objective is pursued:

RO4: *Assessing through a scenarios analysis approach how citizen's behaviour affect the level of separated collection and GHGs emissions.*
Definition of the Marginal Environmental Benefit

Analytical models are more suitable for technicians and waste management practioners. Complexity of the economic and the environmental evaluation of waste management system limits the adoption of analytical tools by policy makers. Indeed, for a policy maker, not delved into technical detailed of such an issue, a user-friendlier tool with a different type of input/output information is more advisable.

RQ6: *How should user-friendly tool be designed for a local-policy maker who seeks to have insights into potential effects of different waste management policy mainly on GHGs and monetary savings?*

Coherently, the following research objective is pursued:

RO5: *Development of an Artificial Neural Network- based decision support tool for the assessment of system arrangements as well as prediction of direct/avoided emissions and financial flows.*

A particular research field concerns the development of tools for environmental evaluation in terms of the carbon footprint index of waste management practices. It reveals increasingly attractive as demonstrate by the number of works developed in recent years.

The U.S. Environmental Protection Agency (EPA) developed the Waste Reduction Model (WARM) to assess savings in greenhouse gas (GHG) emission resulting from waste management practices. The tools works on a collection system already defined. To allow the GHGs emissions evaluation, the users enter the amount of waste flows handled for the different treatment options and by means of material-specific emission factors for each management practice, GHGs emissions and energy savings are calculated. Furthermore, in the context of European project "Zero Waste", a carbon footprint tool for municipal solid waste management is developed (Sevigné Itoiz et al., 2013). The calculator is addressed to solid waste managers, academics and consultants. According to the IPCC guidelines, the calculator allows to inventory and to monitor GHGs emissions starting from the total amount of waste generated, waste composition, waste fraction collected, biogas captured in landfill.

Despite the collection phase is recognized as a key factor in both technical performance (quantity and quality of the collected flows) and environmental impact, none of the tools analysed allows evaluating the effects of changes in its on system performance. Indeed, Both of them start from a well-defined collection system or flow.

Providing "smartness" to modern society is emerging as a strategy to ensure 'circularity' at city level. Although the steady progress already experienced, greater efforts can be done to involve ‘smart actors’ who cooperate in decision-making on public or social services. Stakeholders include citizens whose behaviours strongly affect system performance. Indeed, despite a willingness to make personal behaviour changes to reduce their climate impact, individual may lack the knowledge to make effective choices and to be aware of the consequence of their behaviour (Kim et al., 2009). Communication tools are therefore necessary. In this field, experiences are still lacking.

RQ7: *It is possible contributing to 'smartness' through a citizen-based tool?*

Coherently, the following research objective is pursued:

RO6: *Developing of the web-app-‘Smart Waste-Carbon Footprint Calculator’ – as smart tool to plan and to monitor with twice interface customized for citizens and decision makers.*

The different research questions and relative objectives are closely related to each other as shown in the in Figure 3.

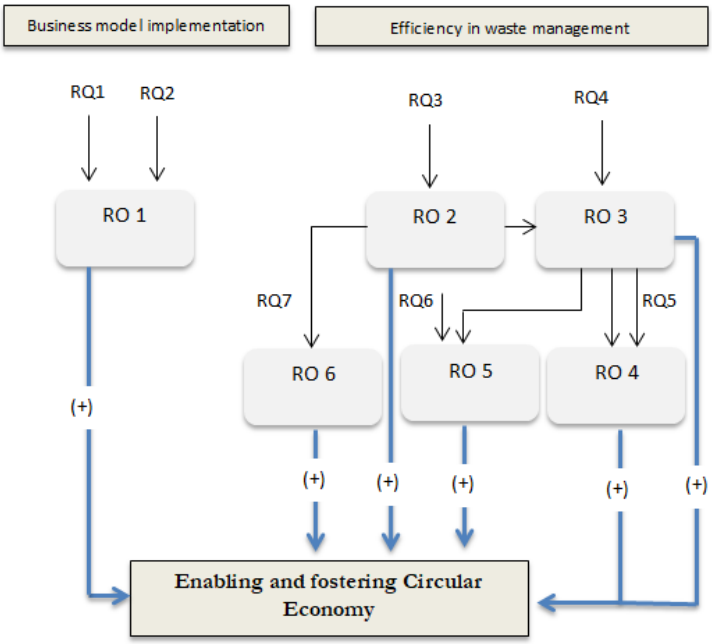


Figure 3- Overview of Research Questions, Research Objectives and relationship

Further details about each RO are faced in specific chapter, as listed in table below. Details about research methodology adopted are faced in each chapter addressing the relative research question being specific for each.

Chapter 2

FOSTERING CIRCULAR ECONOMY THROUGH NEW BUSINESS MODEL: A FUZZY COGNITIVE MAP

2.1 Introduction

This Chapter addresses RQ1-RQ2 and pursues RO1.

As highlighted in Chapter 1, a literature gap exists. Thus, this Chapter is devoted to evaluate impacts on a supply chain level considering all the actors involved in the transition from an ownership-based to a product-as-a-service. The analysis is carried out developing a fuzzy cognitive map (FCM) model to quantify direct and indirect effects on social, economic, environmental and technical dimensions due to the adoption of a Product-Service-System (PSS) business model. The test case of a large appliance product, i.e. washing machines is evaluated. The choice of this particular segment is supported by bibliographic analysis. The robustness of the proposed methodology is such that it can be replicated for the same purpose in other segment of the EEE market looking at the peculiarity of the segment.

Firstly, the role of closed-loop schemes and PSS business model is investigated (Section 2.2). Both the traditional and the leasing supply chain models are analyzed in Section 2.3. Here, the building of the FCM as well as key drivers and their causal relationships affecting systems' performance are identified and discussed. Scenario analyses results are presented in Section 2.4. Final remarks are addressed in Section 2.5.

2.2 Theoretical background

The scientific interest about the Circular Economy paradigm has been growing in the last decades: several applications have been studied, some more successful than others, and some barriers and challenges have been identified (Winans et al., 2017). Recent studies identified the main enabling factors to facilitate the transition towards Circular Economy, among which closed loop logistics models and new service-based and function-oriented business models play a significant role.

In this section, the role of closed-loop schemes and Product-Service-System (PSS) business model as enabling action for the implementation of CE has been investigated.

2.2.1 The role of closed loop and of Product-Service-System towards Circular Economy

A recent review on reverse logistics and closed-loop (CL) systems outlines the need for integration of environmental objectives in the design and assessment of closed-loop models (Govindan et al., 2015).

On a strategic level, the role of closed-loop production systems in the realization of both economic and environmental goals is underlined by Winkler (Winkler, 2011), who stresses in particular the potential of sustainable supply chain networks (SSCN) in the transition to a CE. The author underlines the importance of realizing closed-loops at a supply chain level, as single companies cannot implement effective closed systems on their own. Similarly, Sheehan et al. (Sheehan et al., 2016) explore the role of closed material loops for the implementation of CE, analysing material waste forms and their interdependencies. From this study, a causal-loop diagram is derived for future analysis through system dynamics simulation, as a tool to support decision-making in waste minimization. Jawahir and Bradley (Jawahir and Bradley, 2016) outline the lack of technological elements to implement CE strategies, and propose the framework of sustainable manufacturing as a starting point to realize closed-loop systems based on the 6-Rs (reduce, reuse, recycle, recover, redesign, remanufacture).

A few case studies on specific sectors have also been analysed in the last years. Reuter (Reuter, 2016) highlights the importance of the metallurgic sector for CE, underlining the necessity of exploring new business models to realize effective closed-loop systems. (Accorsi et al., 2015) focuses on the design of a closed-loop network in the furniture industry, considering economic and environmental optimization functions in a mixed-integer linear programming model, and including all the actors of the supply chain, from raw materials suppliers to recyclers and disposal centres. The authors aim at providing some guidelines to practitioners for the transition to a CE scenario. (Niero and Olsen, 2016) compare the environmental impacts of a closed loop versus a traditional recycling strategy for aluminium cans through LCA, elaborating some recommendations to improve the environmental performance of this sector towards the implementation of CE strategies. On the same case study, Niero et al. (Niero et al., 2016) explore and compare the efficacy of the Life Cycle Assessment (LCA) methodology and the Cradle-to-Cradle (C2C) certification in supporting the implementation of CE strategies, identifying both their benefits and challenges. (Richter and Koppejan, 2016) analyse the application of the Extended Producer Responsibility (EPR) as a tool to support eco-design and closed-loop for gas discharge lamps, in a CE perspective. Their study reveals best practices in the sector in the Nordic countries, and identifies some key challenges for the implementation of EPR strategies. In (Sinha et al., 2016) a system dynamics simulation model is proposed to explore the main paths and drivers for closing material flow loops in the global mobile phone product system. They identified four main drivers that could possibly support the transition to circular economy closed-loop systems: (i) improving collection systems, (ii) longer mobile phone use time, (iii) improved informal recycling in developing countries and (iv) shorter mobile phone hibernation time. Finally, (Silva et al., 2016) describe three case studies of policy support to sustainable waste management (San Francisco area, Flanders and Japan), comparing the policy directions observed and suggesting some further developments in policy, planning and behaviour change to realize effective closed-loop systems.

Focusing on the potential of PSS to support CE strategies, the diffusion of such a business model can indeed reduce material consumption and the related environmental impacts, while customer loyalty and company revenues are expected to increase. In his recent review about PSS, Tukker underlines the high potential of this business model in the journey towards CE (Tukker, 2015). However, he also points out that PSS are not by definition more resource efficient and sustainable than the product sale: it is necessary to evaluate the sustainability of such systems since the design phase, to ensure their economic, environmental and social viability.

Moreover, some main barriers in the diffusion of PSS (such as the consumer's need to keep control over the product) were identified. (Lewandowski, 2016) provides an overview of different possible circular business models, including PSS, contributing to the definition of a framework for supporting companies in the business model design phase. In (Catulli and Dodourova, 2013) is explored the challenges related to the adoption of PSS, as well as the benefits entailed, underlining the necessity of an innovation-oriented approach for businesses, institutions and policy makers. They identify cooperation as one of the keys to a successful PSS business model.

Some examples of CE-oriented PSS are also provided in literature. (Iung and Levrat, 2014) describe and analyse the role of maintenance in PSS offers as a way to guarantee service continuity towards circular economy paths. (Johansson et al., 2016) describe the PSS business model for the urban mining segment, as a path towards circularity, defining the key topics to address and a set of guidelines to follow when developing the business model. Lelah et al. (Lelah et al., 2011) discuss the use of a machine-to-machine PSS solution in glass waste collection for recycling, analysing its main environmental impacts and benefits through LCA.

2.2.2 Circular economy business models in EEE supply chain

The (Ellen MacArthur Foundation, 2013) reports that new PSS business models based on refurbishment and product life extension could be implemented with environmental benefits in several sectors, such as the automotive or the EEE. This last one, in particular, is considered crucial both for the volumes of e-waste generated annually, with a forecasted annual growth of 4-5%, which often contain hazardous substances, and for the high value entailed in the materials used (Elia et al., 2016b; Elia and Gnoni, 2015). For these reasons, policy pressures have been pushing the industry to search for sustainable solutions for the management of Waste from EEE (WEEE). As an example, the new European directive released in 2012 (2012/19/EU) prescribes a change in the collection target, which was so far of 4 kg/capita, switching to a floating target of 45% in weight of the EEE sold in the three preceding years.

Reverse logistics models are already widely applied for the collection of WEEE, but collection rates are still pretty low: in 2014 the European countries’ average was from 1.5 kg/capita in Romania to 14.9 kg/capita in

Norway (Eurostat, 2016). Moreover, some major changes in the design are needed to allow easier recyclability and remanufacturing of the products (Ellen MacArthur Foundation, 2013).

Several challenges related to reuse and remanufacturing of EEE have been identified in literature (Kissling et al., 2013; Kumar and Putnam, 2008). Some of them could be tackled through the implementation of new circular economy oriented business models, such as leasing (Ellen MacArthur Foundation, 2013). This solution involves two of the main pillars and enabling actions of CE: PSS use-oriented business models, contributing to the dematerialization of the offer (Mont, 2002), and closed-loop models, aiming at increasing products and materials recovery (Elia et al., 2016a). In particular, the following barriers could be overcome through business model innovation:

- need for sufficient volumes and quality of used products;
- unpredictability of return rates;
- uncertainty of demand;
- competition from the informal sector and the illegal market;
- uncertain economic profit;
- lack of information systems to support take-back.

A leasing based business model, where the user has access to the product for a predefined amount of time (e.g. 5 years), would indeed allow the producer to decrease the uncertainties related to return rates and volumes, while the benefits of a maintenance service can increase the quality of the products collected at the end of the contract. At the same time, take-back would be guaranteed, decreasing the diversion to illegal market and informal sector. The economic profit for the producer should be deeply analyzed to ensure the viability of such a model.

Among the actions identified as enablers for the implementation of CE strategies, organizational changes are widely acknowledged to be a fundamental and critical step for successful CE strategies (De los Rios and Charnley, 2016), as a way to reduce the environmental burden related to the product, while extending the product and/or its components lifetime (Tukker, 2015).

Despite the interest shown towards the application of closed-loop and PSS as suitable ways for a transition to CE, none of the works analysed consider the joint effects of both tools on a supply chain level, and only a few of them attempt to evaluate the impacts of these actions on sustainability. Moreover, researches about the implementation, including the economic and social advantages for companies and customers, is still lacking, as well as assessment tools to verify the effectiveness of circular strategies, although it is necessary for a successful implementation of circular models (Elia et al., 2016a; Winans et al., 2017).

Indeed, the overall impacts of such models on the environmental, economic and social perspectives are not clear, as several uncertainty factors arise with the implementation of non-ownership models. Although the potentialities of PSS to foster sustainability paths have been widely recognized, researchers have been raising concerns about the rebound effect, which might cause an overestimation of the impact of new technologies or business models on sustainability (Sorrell and Dimitropoulos, 2008; Weidema B P, 2008). In particular, research on the rebound effect in the PSS context is still in its early stage (Allais and Gobert, 2016; Kjaer et al., 2016). Focusing on the application context, although the high value of end of life materials from WEEE and the critical importance of this waste flow, research about business model innovation oriented to circularity in the EEE sector is lacking. The aim of this chapter is to contribute to fill the gap, proposing the joint application of two CE pillars to this sector: PSS and closed-loop models. To understand the viability and the benefits and challenges related to this business model proposition, an assessment of the impacts of this solution on all the actors involved in the EEE supply chain is needed. To do this, the test case of the washing machines segment is explored in the following sections.

2.3 Materials and method

2.3.1 The circular business model proposed

The washing machines market is currently heavily dependent on product lifetime and prices. Similarly to other mass customized products, one of the main drivers influencing the customer's choice is the price: very often, this pushes the user to opt for entry-level machines. However, considering the operating cost in the long period, high-end machines tend to be more efficient, with a user cost per washing cycle 55% lower than entry-level devices (Ellen MacArthur Foundation, 2013). Despite this, traditional ownership-based business models orient the customers towards entry-level machines, which are usually characterized by a short lifetime and lower value components. Switching to leasing offers, where the user can defer the payment through monthly instalments, could facilitate the access to high-end products, while guaranteeing a stricter control of the manufacturer over the product during its lifetime.

Starting from these premises, a new supply chain (SC) model for washing machines is proposed, based on the integration of a leasing-based PSS and closed loop models for managing the reverse logistics flows. Figure 1 shows the actors and the main processes involved.

The PSS offer would be based on a leasing contract that enables the customer to benefit from a product for a fixed amount of time (e.g. 5, 10 or 20 years) removing the cost barriers and distributing the costs over time. A maintenance service would provide interventions when necessary, as well as programs upgrading after the first sale, which would contribute to increase the energy efficiency with minimal effort. A closed-loop strategy would be crucial to manage the reverse logistics of the model, collecting the used devices at the end of the leasing contract and recovering the components and the materials for recycling and remanufacturing, when economically viable. Refurbished products could be addressed to a secondary market, while the materials recovered could be used again for the production of new washing machines. Thus, a new supply chain model for washing machines is proposed based on the integration of leasing based model for the direct flow of materials and closed loop models for managing reverse logistics flows of waste.

Actors and processes are depicted in Figure 4. The main actor of this supply chain is the Service Provider Company (SPC), which is directly involved in managing leasing contracts, as well as maintenances activities; it completely replaces the 'traditional' retailer, which is usually responsible only of sale activities. Since in the proposed SC no redemption of leasing agreements would be possible for both households and commercial users, the leased product is collected after the use phase. A third party Logistic Service Provider (3LSP) would be designated for transportation and collection processes. The collected products are then sent to refurbishment processes managed directly or indirectly from the SPC. Refurbishment processes usually relate replacement of the common break points (motor, pump, bearing etc.) or improvements in energy efficiency programs enabling the refurbished products leased for consecutive times. Indeed, the SPC is also responsible for managing the second-hand products leasing contracts too. When the refurbishment processes are not viable for technical or economic reasons, end of life washing machines are recycled. SPC is responsible also for secondary raw materials markets and scrap disposal.

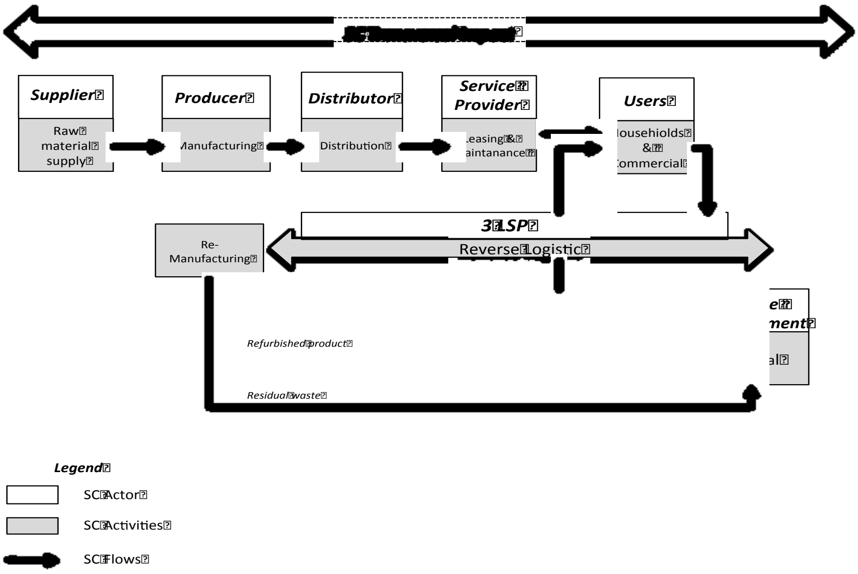


Figure 4 - The leasing-based SC

2.3.2 Study methodology

To overcome the current literature gap, it is proposed a Fuzzy Cognitive Map (FCM) to quantitatively asses how new business model in CE perspective, as the one proposed in the previous section, could contribute to increase the overall effectiveness of the Electric and Electronic Equipment (EEE) supply chain from a sustainability point of view. The FCM methodology allows evaluating interrelated impacts due to multiple sources of factors: this is the case in analysis where the simultaneous presence of leasing based business model and a closed loop reverse logistics model are jointly applied to transform the traditional EEE supply chain in a more circular one. Next to the three widely recognized dimensions of sustainability (economic, social and environmental), a third category has been considered including the more technical aspects of the

PSS implementation, which also have some indirect influence on the three dimensions of sustainability.

2.3.2.1 Fuzzy Cognitive Map: main features

Fuzzy Cognitive Maps are a modeling methodology based on exploiting knowledge and human experience to both design and control complex and dynamic systems, drawing a causal picture to represent the model and the behavior of a system (Groumpos, 2010). Originally introduced by (Kosko, 1986) as an extension of the forerunner cognitive maps proposed by (Axelrod, 1976), FCMs are directional diagrams to represent causal reasoning. FCMs fuzziness allows the forward and the backward direct and indirect systematic causal propagation assessment (Glykas, 2010; Henly-Shepard et al., 2015).

As depicted in Figure 5, FCMs consist of three main elements:

- concepts (*n*): they represent the i-th nodes of the graph C_i and stand for variables describing features and behavioral characteristics of the analyzed system (C.D Stylios, 2004);
- arcs: the directed arcs stand for causal interactions between C_i and C_j concepts;
- relative weights, w_{ij}: each w_{ij} varies from [-1; 1]; it represents the degree of influence that the value of C_i has on the value of C_j (Papageorgiou and Stylios, 2008). Three possible interaction exist: *positive causality* ($w_{ij}>0$), i.e. the increase of the concept C_i causes the increase of the concept C_j; *negative causality* ($w_{ij}<0$), i.e. the increase of the concept C_i causes the decrease of the concept C_j; and, finally, *no influence* if $w_{ij}=0$.

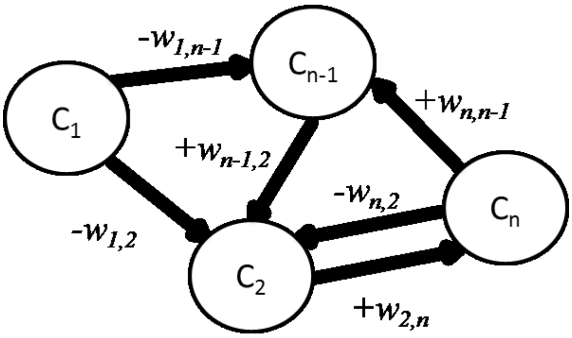


Figure 5: Example of an FCM representation

According to graph theory, FCM can be converted into a *(n x n)* square matrix '**W**', i.e the Adjacency Matrix, where both the rows and the column represent the *i-th* concept and each cell represents the weighted influence existing between concepts (Özesmi and Özesmi, 2004). In a FCM, it is possible to recognize transmitter variables (also called drivers, forcing functions, sources), receiver variables (or utilities, ends, sinks) and ordinary variables (Harary et al., 1965; Özesmi, 2006) by evaluating their outdegree and indegree. The outdegree shows the cumulative strengths of connection exiting the concepts, while the indegree shows the cumulative strengths of connection entering the concept (Özesmi, 2006). Consequently, transmitter concepts have a positive outdegree and zero indegree. On the opposite, receiver concepts have a positive indegree and zero outdegree. A positive indegree and outdegree characterizes the ordinary concepts. The centrality index, calculated from indegree and outdegree, represents the contribution of the concept in the map and how it is connected to others.

The column matrix A^t represents the value of each concept at each iteration step *t* within the range [-1;1]. It is calculated through equation (1) where *f* is the threshold function.

$$A^t = f(A^{t-1} + A^{t-1}W) \qquad (1)$$

Usually, two kinds of threshold function are employed, depending on the methods used to describe the concepts (C.D Stylios, 2004). Further details about mathematical description of an FCM are described in (Papageorgiou and Kontogianni, 2012; Papageorgiou and Salmeron, 2014).

It is widely recognized that conventional modeling methods slightly contribute to design and control complex dynamical systems with high dimension and a variety of variables and factors. FCMs have been proposed for complex systems using existence knowledge and human experience and having learning capabilities and advanced characteristics such as strategies detection and impacts identification over the time (Papageorgiou and Stylios, 2008). Coherently, FCMs are identified as the most appropriate methodology to investigate an unexplored and promising complex panorama as the ones of CE strategies in EEE sector.

2.3.2.2 Developing a FCM for EEE leasing based business model

The FCM development greatly influences its success in modeling. According to (S. Gray et al., 2014), a FCM can be obtained through a '*list of standardized concepts*' or through '*freely associated concepts*'. While the standardization of concepts entails asking experts to identify connections among the same list of predefined concepts, thus constructing their individual FCMs, the elicitation through free association of concepts entails asking experts to previously identify concepts to construct their own map. The standardization method reduces researchers' efforts in subjectively categorizing and reducing the large quantity of concepts typically resulting from FCM elicitation using free association. Furthermore, the use of standardized concepts may scaffold participants and promote social learning as a result of the group discussion and through the model validation process.

It is deemed the *'standardization'* procedure suitable for the construction of the case study FCM.

The first step of the proposed FCM model has been to outline the concepts that compose the FCM. This identification is based on a literature analysis, starting from the case study presented by the Ellen MacArthur Foundation and other works on PSS.

The consistency of the overall concepts has also been checked through an experts' analysis. A summary of the concepts is reported in Table 1, where for each concepts identified, the impact category is also pointed out. Evidences in literature are listed too.

Table 1- FCM Concepts classified for SC level and impact category

SC level	FCM Concepts	Impact category	References
Suppliers	Suppliers' orders generation rate (C1)	Economic	-
Producer	Raw materials flow mass rate (C2)	Environmental	(Baines et al., 2007; FORA, 2010)
	Remanufacturing processes cost (C3)	Economic	(Mont, 2002)
	Net recovered materials rate (C4)	Economic	(Mont, 2002)
	Landfilling cost (C5)	Economic	consequence of waste generation
	Producer profit (C6)	Economic	(Baines et al., 2007)
	Refurbishment products volume (C7)	Technical	consequence of leasing
	Recycling rate (C8)	Environmental	(Mont, 2002)
	Extension of product lifetime (C9)	Technical	(Mont, 2002)
	Production outputs rate (C10)	Technical	consequence of lifetime extension
Distributor	Traceability and take-back forecasting effectiveness (C11)	Technical	consequence of leasing

Service provider	Leasing contract rate (C12)	Economic	-
	Service provision and maintenance rate (C13)	Technical	consequence of leasing
3LSP	Reverse logistics rate (C14)	Technical	(Baines et al., 2007; Mont, 2002)
	3LSP commissions generation rate (C15)	Economic	consequence of reverse logistics service
Secondary market	Refurbished products sold rate (C16)	Economic	
User	Illegal market size (C17)	Economic	consequence of traceability
	Ownership product rate (C18)	Technical	(Baines et al., 2007; Demyttenaere et al., 2016; FORA, 2010)
	Customer cost (C19)	Economic	(FORA, 2010)
	Customer service level (C20)	Technical	(Baines et al., 2007)
	% of products used for an efficient time period (C21)	Technical	-
	Availability rate of high-end machines (C22)	Social	(Baines et al., 2007; FORA, 2010)
	Spread rate of technologically updated products (C23)	Technical	(FORA, 2010)
Waste management	Waste generation rate (C24)	Environmental	(Baines et al., 2007)
Transversal impacts	Tax incentives (C25)	Economic	(FORA, 2010)
	Emissions reduction rate (C26)	Environmental	(Baines et al., 2007)
	Public consciousness and involvement in CE (% of people) (C27)	Social	-
	Leasing public acceptance (% of people) (C28)	Social	consequence customer cost, equity
	Normative compliance (C29)	Technical	consequence of recycling

Once the concepts have been identified, the causal relations and relative weights between concepts have to be determined, thus constructing the map and the relative adjacency map. For its coding, it was required to a set of experts to find the causal interconnections and related strengths using the list of *'standardised concepts'* provided. In assigning weights, the membership functions explained in (Stylios and Groumpos, 2000) are followed. The individual cognitive maps produced are then coded into a 'unique' FCM by averaging each w_{ij}. As an example, $w_{3,6}$ is posed equal to -0,80 since when the 'Refurbishment Process Cost (C3)' decreases, the 'Producer Profit (C6)' increases. According to aforementioned membership functions, the casual influence by which the 'Refurbishment Process Cost' influences the 'Producer Profit' is negatively very strong meaning an influence below to -75%. The FCM developed is shown in Figure 6, while the related adjacency matrix is reported in Table 2.

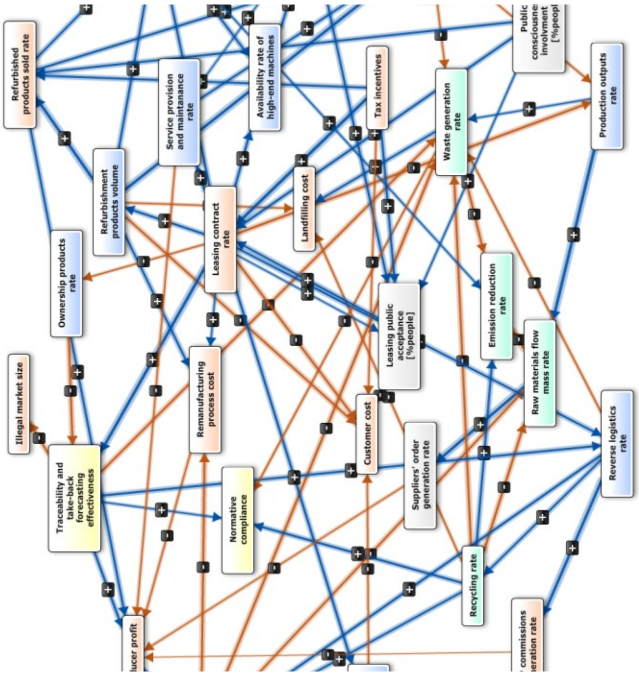
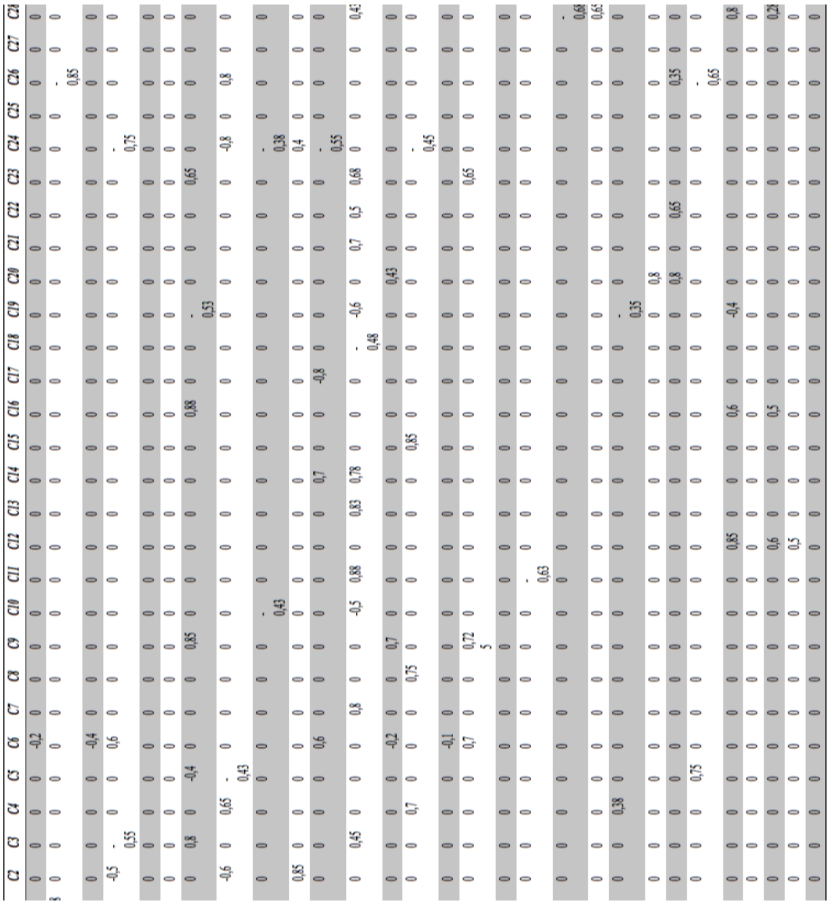


Figure 6- FCM: identification of causal relationship and relative weights



C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28
0	0	0	0	-0,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,85	0	0
0	0	0	0	-0,4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-0,5	-0,55	0	0	0,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,75	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0,8	0	-0,4	0	0	0	0,85	0	0	0	0	0	0	0,88	0	0	-0,53	0	0	0	0,65	0	0	0	0	0
-0,6	0	0,65	-0,43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,8	0	0,8	0	0
0	0	0	0	0	0	0	0	-0,43	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,38	0	0	0	0
0,85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,4	0	0	0	0
0	0	0	0	0,6	0	0	0	0	0	0	0	0,7	0	0	-0,8	0	0	0	0	0	0	-0,55	0	0	0	0
0	0,45	0	0	0	0,8	0	0	-0,5	0,88	0	0,83	0,78	0	0	0	-0,48	-0,6	0	0,7	0,5	0,68	0	0	0	0	0,43
0	0	0	0	-0,2	0	0	0,7	0	0	0	0	0	0	0	0	0	0	0,43	0	0	0	0	0	0	0	0
0	0	0,7	0	0	0	0,75	0	0	0	0	0	0	0,85	0	0	0	0	0	0	0	0	-0,45	0	0	0	0
0	0	0	0	-0,1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0,7	0	0	0,725	0	0	0	0	0	0	0	0	0	0	0	0	0	0,65	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	-0,63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,68
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,65
0	0	0,38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,35	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,8	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,8	0	0,65	0	0	0	0,35	0	0
0	0	0	0,75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,65	0	0
0	0	0	0	0	0	0	0	0	0	0,85	0	0	0	0,6	0	0	-0,4	0	0	0	0	0	0	0	0	0,8
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0,6	0	0	0	0,5	0	0	0	0	0	0	0	0	0	0	0	0,28
0	0	0	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Hereinafter, the main connections are explained. Users can benefit from lower overall costs and wider access to high-end machines. At the same time, the maintenance and upgrading activities on one side increase the customer service level, on the other allow a spread of technologically updated products without buying new devices, also causing an increase in the energy efficiency of the appliances (and consequently lower CO_2 emissions) (Baines et al., 2007; FORA, 2010). Another effect of the leasing-based model would be the increase of products used for an efficient time (time use efficiency), due to the time constraint included in the contract and to the maintenance service that keeps the device in good operating conditions. Increasing the return rate of the products, the illegal market size would also decrease, contributing to a higher normative compliance on a policy level. Finally, the ownership rate would decrease, which might represent a possible barrier to the diffusion of such models (Baines et al., 2007; Demyttenaere et al., 2016; FORA, 2010). This requires further studies on the customer's acceptance of a PSS solution, in order to ensure a successful implementation of the model. All the benefits described would contribute to increase the public acceptance of such a business model, fostering a virtuous cycle. In the user's perspective diagram, product's ownership has not been included, because its impact on the public acceptance of the leasing model is still not clear, as previously explained. A virtuous cycle can be identified regarding the cost for customers, decreasing with the adoption of leasing contracts, which increases the public acceptance, consequently encouraging new leasing contracts. The same dynamic can be observed with the customer service level, increased by the maintenance services, the wider access to high-end machines and the spread of technologically updated devices. A further push to the diffusion of leasing contracts can be reached through the introduction of tax incentives and the diffusion of policy measures for increasing public awareness and involvement in CE issues.

On the producer and distributor's side, a leasing-based PSS would increase traceability and the effectiveness of take-back forecasts, leading to more stable reverse logistics flows and guaranteeing a stronger control on the products' flow and lifecycle (Baines et al., 2007; Mont, 2002). Moreover, allowing an easier recovery of the end-of-life product, which has benefited from a controlled maintenance over the years, this business model ensures a higher quantity and quality of the recovered materials, enabling higher recycling and remanufacturing volumes (Ellen MacArthur Foundation, 2013; Mont, 2002). This would have an impact on the secondary market, which could increase through the introduction of more refurbished devices, and on the waste generation rate (Baines et al., 2007). The extension of the product lifetime would negatively influence the production volumes, and consequently the raw materials flow and the orders to suppliers. Therefore, the higher costs deriving from remanufacturing process, service and maintenance activities and commissions to 3LSPs, would be balanced by the value of materials recovered and the avoided landfilling costs (Baines et al., 2007; Ellen MacArthur Foundation, 2013; FORA, 2010; Mont, 2002). All of these voices have an impact on the company's profit, which needs to be deeply investigated in order to ensure the economic sustainability of the business model proposed. On the producer's side, several economic impacts have an effect on the producer's profit. Positive impacts are given by the increase of reverse logistics flows, therefore of net recovered materials, and the higher volumes of refurbished devices produced and sold. The higher traceability and forecast reliability also represents an economic advantage for the producer, who can manage his resources more efficiently. The decrease of landfilling costs constitutes a further benefit for the producer, as well as the decrease of orders to suppliers (thanks to lower production volumes and higher material flows recovered). On the other side, remanufacturing and service provision costs are expected to increase, as well as logistics providers' commissions.

Looking at the other impacts on sustainability, the environmental, social and technical benefits of the new business model are even clearer. The higher material recovery causes a decrease in raw materials extraction, while recycling increases and less waste is produced. This concurs in decreasing the emissions, which are also influenced by the spread of technologically updated (therefore more energy efficient) products. A better time use of the product and its lifetime extension also contribute to increase material recovery and decrease waste production. Moreover, on the social side, the illegal market size decreases thanks to the efficient reverse logistics. This, together with emission reduction and waste minimization, contributes to reach a higher compliance of the normative enforced.

After the map is drawn and the adjacency matrix is coded, structural metrics can be assessed. Map and components structural metrics are shown in Table 3. Starting from the total number of both components (29) and connections (72) identified, the density index is evaluated showing how connected is the map (Hage and Harary, 1983). The map density is 0,09 consistent with value observed in literature (Klein and Cooper, 1982; Malone, 1975). The complexity score calculated as the ratio between receivers and transmitters (S. A. Gray et al., 2014; Özesmi and Özesmi, 2004), is an indicator of how the system is perceived to be complex. The complexity index for the developed map is equal to 2,5 as well as the average connections per component. The indegree and the otdegree have been evaluated to identify drivers, receivers and ordinary variables as well as to establish the centrality for each component (Section 2.3.2.1).

Two transmitter components have been identified:

- Tax incentives (C25): it represents a ‘user incentive-scheme’ to foster the adoption of a new business model based on leasing contracts.
- Public consciousness and involvement in CE (C27): it jointly represents an awareness and commitment measure of users in CE milestones influencing their inclination in the adoption of new business model.

These variables are the policy variables as they could be modified by policy makers with the aim of improving the economic, environmental, technical and social performance of the analyzed supply chain.

Receiver variables reflect the totality of causal relations between ordinary variables and of strategies implemented for transmitter variables; five receiver concepts have been also identified:

- Landfill cost (C5): It represents the cost incurred to dispose of not recyclable products/components.
- Producer profit (C6): It represents the producer earning due to the production and the sell/leasing of the washing machines.
- Emission reduction rate (C26): It represents the emissions cuts due to recovered and recycled materials flows, as well as to improved energy efficiency programs.
- Normative compliance (C29): it represents the compliance with European directives.
- Illegal market size (C17): it represents an economic and social measure of illegal phenomena affecting the EEE market. The more central concepts are the 'Leasing contract rate', 'Waste generation rate' and the 'Net recovered material value'. Full data about each concept are in Table 3.

Table 3- FCM inference: initial steady state and indexes

COMPONENT STRUCTURAL METRICS				
COMPONENTS	INDEGREE	OUTDEGREE	CENTRALITY	TYPE
C1	0.88	0.3	1.18	ordinary
C2	1,95	1.73	3.68	ordinary
C3	1.8	0.8	2.6	ordinary

C4	1.73	2.25	3.98	ordinary
C5	1,58	0	1,58	receiver
C6	2,86	0	2,86	receiver
C7	0,8	4,11	4,91	ordinary
C8	0.75	4.03	4.78	ordinary
C9	2.28	0.81	3.09	ordinary
C10	0,92	1,25	2,17	ordinary
C11	1.51	2,7	4.29	ordinary
C12	1.95	7,60	9,5	ordinary
C13	0.83	1.38	2.21	ordinary
C14	1.48	2.75	4.23	ordinary
C15	0.85	0.18	1.03	ordinary
C16	1.98	1.96	3.94	ordinary
C17	0,8	0	0,8	receiver
C18	0.48	0.63	1.10	ordinary
C19	1.88	0.68	2.56	ordinary
C20	2,03	0.65	2.68	ordinary
C21	0.7	0.73	1.43	ordinary
C22	1.15	0.8	1.95	ordinary
C23	1,98	1,8	3,78	ordinary
C24	3,33	1,85	5,18	ordinary
C25	0	2,65	2,65	driver
C26	2,65	0	2,65	receiver
C27	0	1,38	1,38	driver
C28	2.83	0.5	3.33	ordinary
C29	1.63	0	1.63	receiver

MAP STRUCTURAL METRICS	
Total Components	29
Total Connections	72
Density	0,09
Complexity Score	2.5
Connections per Component	2,48
Number of Driver Components	2
Number of Receiver Components	5
Number of Ordinary Components	22

2.4 Simulation results

The Developed FCM has been then digitized in an FCM software, Mental Modeler (see www.mentalmodeler.org, (Gray et al., 2013) and used to explore different scenarios, in order to evaluate the impact of some possible strategies on the sustainability dimensions all along the supply chain. Two scenarios have been considered:

- Scenario 1: it refers to the baseline scenario where the new business model based on leasing contracts has been introduced without any incentives;
- Scenario 2: it differs from the previous one due to the adoption of tax incentives and policies oriented to increase public consciousness and involvement in CE issues (C12, C25 and C27) for supporting the new business model.

The results obtained for both the scenarios are shown in Figure 7.
The introduction of leasing contracts in scenario 1 is compliant with four of the five objectives introduced as a performance measurement, causing a decrease of landfilling costs and illegal market size, while increasing the emission reduction rate and the normative compliance. This is mainly due to a lower waste generation rate. The combination of a more efficient reverse logistics with an increase in traceability effectiveness allow to divert the used products from the illegal market, increasing, at the same time, the recycling rate and the net recovered material rate. On the economic side, it can be noted that the producer profit does not change a lot by introducing the new business model; this is mainly due to increased costs to remanufacturing and service provision, which compensate for the lower production volumes and the sales of refurbished products.

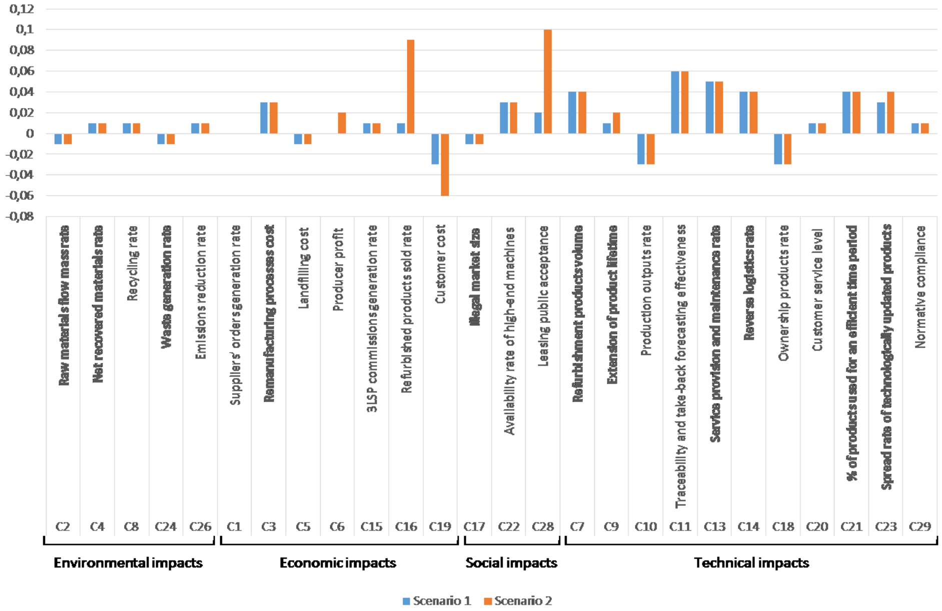


Figure 7- FCM Scenarios analysis results

Differently, in scenario 2 financial and social measures to support the introduction of the new business models have been evaluated. On the social side, the wider access to high-end machines allows even low-income customers to benefit from good quality products thus saving costs. Thus, the introduction of tax incentives and public awareness oriented policies can support better the economic feasibility of the new business model. Due to a huge increase of the refurbished products sales compared to scenario 1, the producer profit increases thus amplifying benefits of the new business model. At the same time, the customer cost decreases. Two other components are affected by the policy measures introduced: the extension of the products lifetime and the spread of technologically updated products, due to the increase of refurbished products sold. While most of the technical, social and environmental impacts are confirmed in both scenarios, the introduction of incentives in scenario 2 seems to boost the economic sustainability of the business model, at least in the starting phase. Both the cost for the customer and the producer's profit would benefit from the measures considered, increasing the market profitability and the public acceptance of the model.

Considering the complexity of the innovation at the supply chain level and according to these results, it can be suggested that a policy oriented to financial and motivational support could increase sensitively the effectiveness of the model proposed. Summarizing, on one side, this analysis confirms the positive benefits expected from the implementation of a PSS closed-loop model in the washing machine segment on the four dimensions considered. On the other side, it outlines quantitatively the potential contribution of such policy measures and how they could significantly be used to support the transition to use-based business models.

2.5 Final remarks

A literature review has highlighted the lack of instruments for the impact assessment of CE strategies, in particular related to the introduction of the two tools described, as a few works explore in detail the role of enabling actions for the implementation of CE on a supply chain level. Consistently, the impact of a CE strategy based jointly on business innovation through PSS and closed-loop schemes on the sustainability dimensions of a supply chain has been explored. Starting from a case study proposed by the Ellen MacArthur Foundation on the washing machines segment, a new circular business model based on leasing and product recovery and recycling has been described. The main impacts on the configuration of the SC and on its actors were identified through a literature analysis and classified. To understand the effects on economic, environmental, social and technical performance due to a shift from a traditional ownership-based business model to a leasing-based business model for washing machines, a FCM is developed. Results obtained witness the robustness of the developed FCM in the evaluation of the forward and the backward systematic causal propagation for the circular economy strategies detection. Starting from the transmitter variables identified in the map ('Tax Incentives' and 'Public consciousness and involvement in CE'), two different scenarios have been evaluated. Simulation solutions stress out the great potential of the leasing-based model since the sustainable performances tend to improve in the scenarios analyzed. Allowing a better flows traceability, the introduction of leasing contracts enables the reduction of the illegal market size and increases the recycling rate. These in turns influence (increasing their value) the normative compliance, the net recovered material rate and consequently the emissions cut.

Additional improvements affect the economic aspects: decreasing of both the incurred landfill cost and of the customer cost. The latter could be further improved by introducing targeted policies to improve user awareness and commitment in CE issues, fostering the adoption of the leasing model and considerably increasing the sales of refurbished products. In this case, the producer profit increases too. The lower cost perceived by the users increases their acceptance of the new business model triggering a very 'virtuous cycle'. The wider access to high-end machines also contributes to increase the social sustainability of the model. It is envisaged also the initial need of supportive policy measures to ensure the economic viability for companies.

Chapter 3

MUNICIPAL INTEGRATED WASTE MANAGEMENT SYSTEM: A HOLISTIC FRAMEWORK

3.1 Introduction

This Chapter addresses RQ3 and pursues RO2.

As highlighted in Chapter 1, a research gap exists. In order to develop policy approach enabling the transformation from waste to resource management, the analysis of the waste management practices and related strengths and weakness is considered a necessary step. Due to the aim to provide a thorough panorama, the analysis goes beyond the existing technical and organizational solutions outlining the different options in a much broader view concerning waste collection, treatments and valorization.
Hereafter the systematization of such knowledge to help in the decision making process, the framework leading up to identifying the variables object of evaluation by the public decision maker. Consistently, it is fundamental in the formulation of the optimization model described in the following Chapter. The decision variables have introduced for each level. Both for the operational and the strategic phase, the different solutions have been in-depth analyzed to define the technical and critical features for environmental planning.

Environmental impact due to material handling, storage, and picking operations is a substantially unexplored field of research. A fundamental role is played by the optimal equipment selection. Consistently, a comparison of electric and LPG forklifts based on carbon footprint indicator is carried out. This analysis is led in the optimization model perspective.

In Section 3.2, the different organizational and technological alternatives are discussed. In Section 3.4, an insight into the internal logistics environmental issues is presented.

3.2 Framework for a Municipal Integrated Waste Management System

A Municipal Integrated Waste Management System (MIWMS) includes three main phases: collection, treatments and valorisation. An optimal system design requires a joint evaluation of processes able to pursue a given economic/environmental goal, due to the mutual influence of quality and quantity of waste streams on the process phase. Furthermore, waste quality and quantity should be compliant with material and energy valorisation. In Figure 8, a general framework of a MIWMS is shown. Beyond common practices currently adopted, the framework is referred to technological and organizational options available for each phase of the MIWMS compliant with EU Directives.

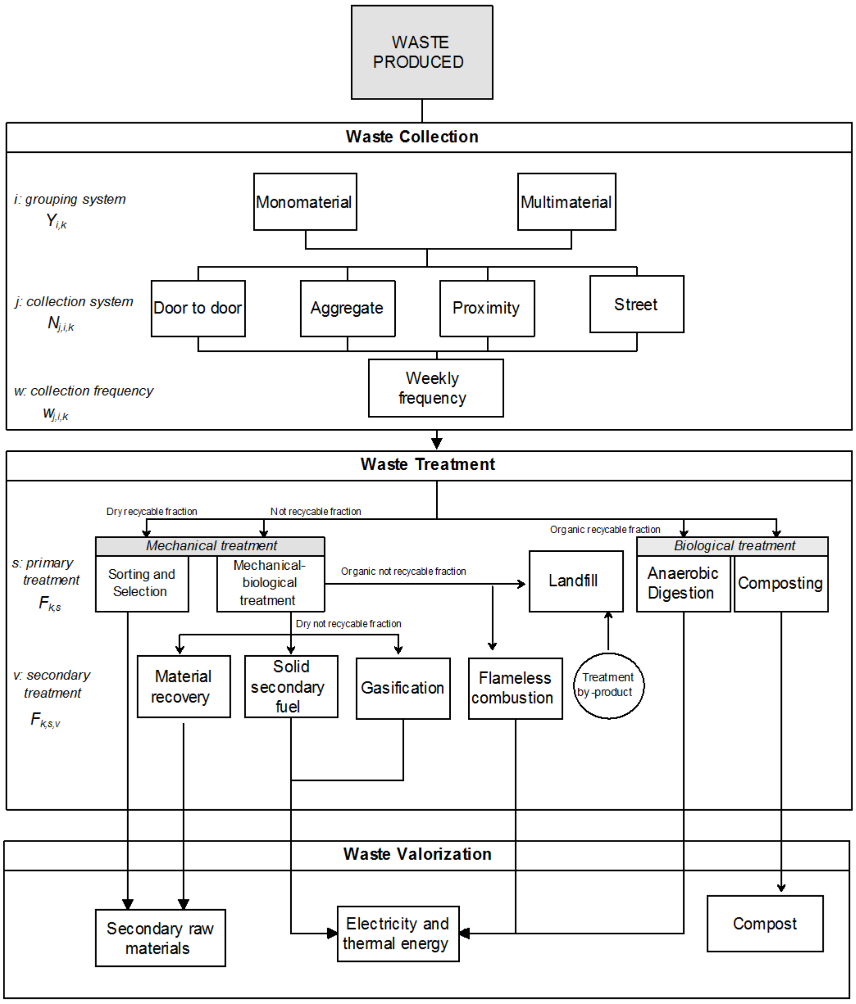


Figure 8 - Five-level framework of Municipal Integrated Waste Management System

3.2.1 Waste collection arrangements

The collection of municipal waste is the core of an Integrated Waste Management system. The way waste materials are collected and sorted affects the set of available feasible technological options for waste recycling as well as biological and thermal treatments. Therefore, existing or potential markets will affect collection and sorting processes. Hence, there is a match between market need and materials collected and sorted (Mcdougall et al., 2001).

Decision variables of collection options relate to waste grouping systems (*i*), collection systems (*j*) and the collection frequency (*w*).

3.2.1.1 Grouping systems features

In the last years, the transition from mono-material grouping system (MoMG) to a multi-material grouping

System (MuMG) is a matter of remarkable interest. In (Fitzgerald et al., 2012) an analysis to assess the greenhouse gas impact of the abovementioned grouping systems is carried out. The analysis shows the potential benefit arising the switching from MoMG to MuMG. The collection of dry recyclable materials is usually carried out by MoMG system (i.e. one stream for each recyclable material like paper, glass, organic waste, plastics and metal cans, etc.). Citizens are requested to sort and stock each household waste stream. Citizens' environmental awareness affects the quality of waste streams and, in turn, the efficiency of recycling processes. In the MuMG system, the onus of sorting moved from citizens to automatic facilities to sort homogeneous materials from a single stream of dry materials. The MuMG system limits citizens' effort thus ensuring increased waste collection rate as well as high and constant quality of waste streams recovered. The MoMG option requires smaller both bins and transport means compared to those required by the multi-stream option. Whilst the MoMG system needs a greater number of collection cycles than those needed by the MuMG system, the latter requires greater energy consumptions of optical sorters and of other automatic equipment. From an environmental point of view, it is therefore necessary to balance advantages and disadvantages of the two grouping systems. Specific fractions have to be managed without mixing materials. It is the case of organic waste since it would negatively affect quality and recycling rate of dry materials. The same line of reasoning applies to glass, which can generate damages to automatic devices as well as contamination of other materials. Technology improvements are expected to lead in the very next future to different grouping options also for organic and glass fractions.

3.2.1.2 Collection systems features

In an urban centre, the collection systems largely depend on both building features and on urban fabric constraints. In (D'Alessandro et al., 2012; Rodrigues et al., 2016a, 2016b) a review of municipal waste management collection systems is provided. Hereinafter, a brief description of the collection systems suitable for each urban area is provided.

The 'door-to-door' collection system (DtD-CS) reveals suitable in case of urban areas with a widespread presence of independent houses with private backyards or direct access from the street (e.g historical centre). The collection is typically carried out by using small transport means and household bins (buckets, bags). The DtD option is suitable when quality of collected materials and users monitoring is pursued. The DtD-CS is not suitable in residential central areas characterized by a significant concentration of users living in high, but not strictly contiguous, buildings. High buildings usually have common areas to place collection containers serving more than one family. In these areas, DtD service would lead to an unpleasant of a huge number of bins on the road board. Managerial and aesthetic drawbacks would be considerable. Therefore in that case, the optimal choice envisages the adoption of the 'proximity' collection system (P-CS) with placement on the public area of containers.

The containers are optionally provided with closure systems with a personal key in order to restrict their use to a number of few users. This option requires high capacity of storage and transport means option and lower effort in waste collection than the DtD-CS. The expected quality of each material tends to reduce since it highly depends on the behaviour of a great number of citizens less subject to a tight monitoring.

A halfway solution between the previous systems is the 'aggregate' collection system (A-CS). This option fits well in case of small urban aggregates of residential buildings with private common areas to be used as waste storage areas for more than one family. The A-CS usually requires higher capacity of both transport and temporary storage equipment than the DtD-CS. The higher capacity of logistic means allows less collection time and shorter routes with reduction in related GHG emissions.

Finally, the street collection system (S-CS) is adopted for a large number of users living in city suburbs with large streets and contiguous residential building (usually blocks without common open areas). A street container usually serves more than 100 families. The low density of containers on the selected area generates a network of conferral workstations developed along the roads with easy viability on which medium-large vehicles can transit. The employment of very large logistic equipment (transport means and bins) allows a reduction in the number of collection routes. The quality significantly varies with collection system adopted. Levels of impurities in collected waste, higher than the maximum values required by the waste market, make recovery processes more expensive or even completely compromised.

3.2.2 Waste treatment processes

Once waste is collected, is necessary to identify the waste treatment that increases the value of the input by means of suitable technologies.

Decision variables of treatment options relate waste fraction addressed to primary treatments (*s*) and to secondary treatments (*v*).

3.2.2.1 Treatments for dry-recyclable fraction

Sorting and selection processes are the treatments foreseen for the dry recyclable fraction. The aim is to separate, to a less o greater extent, different recyclable materials from contaminant in waste flow making recovery worthwhile.

Mechanical selection processes are based on automation and technology innovation. Over the last years, the main technological innovations are due to optical sorters. Optical sorters are mainly employed for plastics sorting. Plastics packaging involve many different polymers and would be neither reasonable nor appropriate to require citizens this degree of separation in plastic collection. By means of spectrometer, the optical sorter recognizes the polymer and, by blowing nozzles conveys it separately. The higher degree of separation ensured by these technologies allows entering the market with products with greater economical and environmental potential value. The spread of that automated process reshapes the role of manual sorting. Indeed, manual sorting can occur at the beginning of the process to remove any material that may damage equipment (i.e heavy wire rope, industrial chain, etc…) and at the end for a flow final quality control. (Ramasubramanian et al., 2008; Safavi et al., 2010) provides a more comprehensive description of general sorting techniques.

For MoMG, the sorting process is easier due to the upstream selection of citizens. For the multi-stream grouping system, the first phase of the sorting process aims to obtain homogeneous flows from the one stream of dry recyclable materials. Ever since, it proceeds with a deep selection for a specific fraction. The different collection systems detailed in section 3.2.1.2, influence the quality of inflows in sorting equipment. From an environmental point of view, the more complex and automated is the process, the greater will be its energy unitary consumptions. The higher volumes collected with the multi-stream grouping system, the higher facilities' total energy consumption. In turn, the higher consumptions cause greater GHGs emissions. On the other hand, the higher quantities of recovered materials cause higher avoided emissions.

3.2.2.2 Treatments for the organic fraction

Composting and anaerobic digestion are the main treatments for the organic recyclable fraction processes.

Composting is an aerobic process that uses microorganisms to oxidize organic waste to carbon dioxide and water vapour. A humus-like residue is left that is then used as a soil conditioner in agriculture or gardening. The use of compost may have beneficial effects on greenhouse gas fluxes by replacing other products like fertiliser and peat and may also lead to increased storage of carbon in the soil (carbon sequestration). Efficient source-separation of organic waste, strictly connected with collection systems, affects the compost quality and consequently its market value.

The conversion of high moisture content and lower heating value biomasses by anaerobic digestion leads to a gaseous energy carrier containing methane and carbon dioxide (biogas), with a reduced solid residue (digestate). The digestate is subjected to maturation by composting. Technical process details are in (Malpei and Gardoni, 2007). Biogas in mainly used for Combined Heat and Power (CHP) application. In (Massaro et al., 2015), an evaluation model is developed to assess anaerobic digestion economic feasibility, without reducing social and environmental benefits. In (Wang et al., 2014), an LCA analysis is carried out to assess sustainability performance of a large-scale plant. Many biogas upgrading processes are developed to upgrade biogas in bio methane for both vehicle fuelling and for in feeding national grids

(Caponio et al., 2013). In this analysis, the conversion of biogas in electricity and thermal energy is considered. This has a potential benefit in terms of greenhouse gases emissions since it avoids the production of electricity by fossil fuels.

3.2.2.3 Treatment for not-recyclable fraction

Mechanical–Biological Treatment (MBT) is the treatment foreseen for dry and organic residual waste.

Mechanical treatments consist of shredding and sieving to separate dry waste from organic wet waste. A volume reduction of waste stream is also obtained. The biological treatment of the organic fraction, known as bio-stabilization, leads to a biological stable product through processes of bio-oxidation by means of periodic turning and aeration. The biological treatment significantly reduces methane emissions from the landfilled waste, compared with untreated municipal solid waste flows.

Downstream MBT, technological options for dry residual waste include: material recovery sorting, production of refuse-derived fuel (RDF) and gasification. Technological options for organic residual waste include: flameless combustion and landfill.

According to the waste management hierarchy, materials recovery takes priority over RDF production and gasification. Sorting process for material recovery is similar to processes described in section 3.2.2.1, Fractions recovered are addressed to specific consortia for the production of secondary raw materials.

RDF production process separates the combustible fraction from the non-combustible fraction of the residual dry solid waste. A wide range of MSW compositions can be burned without auxiliary fuel. Pre-treatment process is foreseen to minimise moisture content and reduce ash content enhancing fuel quality and improving combustion efficiency. The amount of moisture in solid waste is highly variable and can be significantly changed due to processing, handling and storage (Manser and Keeling, 1996). The calorific value is a function of the carbon content of the material.

Gasification is a thermo-chemical process that converts biomass by partial oxidation into an energy carrier: syngas. Syngas is a mixture of carbon monoxide and hydrogen along with other constituents. The production of syngas is a complex process that depends on several factors including the composition of feedstock, gasifier conditions, temperature and pressure, and the amount and the type of oxidizer (CO_2, air or steam) (Syed et al., 2012). In (Arafat and Jijakli, 2013) , the effect of process temperature is investigated. A comparison between gasification and incineration is also provided. Gasification has a great potential since puts on value the waste stream with a low calorific value, normally disposed of in landfill.

The flameless combustion is a combustion process where the auto-ignition temperature of reactants is lower than the inlet temperature of the principal flow of reactants and higher than the maximum increase of the temperature in the reactor (Cavaliere, 2000). The potential of flameless combustion is in the power generation industry with the main advantage of almost no nitrogen oxide formed. In (Hosseini and Wahid, 2013), the application of biogas in the flameless combustion is investigated. The innovative application of this technique for organic bio-stabilized waste reveals promising.

3.2.2.4 Landfill

The 95% of waste management GHGs emissions come from the landfill (Eurostat, 2014). It has historically relied on the majority of solid waste since the simplicity and the cost-effectiveness of landfilling

(MCDougal, 2001). The Directive 1008/98/CE sets the prohibition to dispose of the waste stream having a low calorific value higher than 13.000 kJ/kg. The recovery materials and the production of RDF comply with this setting. As mentioned in Section 3.2.2.3, the flows have to be bio-stabilized before disposing of to limit methane emissions.

3.2.3 Waste valorisation processes

Waste valorisation processes relate three main opportunities: secondary raw materials production, compost production, electricity and thermal energy production.

3.2.3.1 Secondary raw materials production

Materials recovery starts in the Material Recovery Facilities where paper, plastics (HDPE, PET), glass, metals (ferrous and non-ferrous) and other materials are sorted, baled and bulked and transferred to re-processors that produce marketable materials and products (European Commissions, 2001). Alternatively, some of these materials may also be recovered from un-recycled residual dry solid waste. The recovery allows the production of secondary raw materials replacing virgin raw materials.

3.2.3.2 Compost production

The valorisation of the organic waste separated collected by composting process (see subsection 3.2.2.1) leads to several environmental advantages. The positive environmental contribution of compost allows, in addition to carbon sequestration in the soil, indirect benefits such as partial replacing of chemical fertilization avoiding the consumption of fossil fuel for the fertilizers' production. Moreover, the use of compost improves the soil workability that results in a saving energy in processes (Vismare et al., 2008).

3.2.3.3 Electricity and thermal energy production

The production of electricity and thermal energy from waste usually takes place in Combined Heat and Power Plant (CHP). In this plant production of energy occurs in two sections placed in cascade. The high temperature section produces mechanical energy (then transformed into electricity) and the low temperature section provides thermal energy. The energy production by waste stream, usually referred as 'Waste to Energy', allows avoided emissions due to the same amount of energy produced by fossil fuels.

3.3 Inbound logistics of waste treatment processes

As highlighted in the Section 3.1, in order to analyze in detail each 'block' of this MWIMS framework to define the optimality of solutions both on the single and the global level, the role of internal logistics in the systems is analyzed too.

3.3.1 Theoretical background

With reference to the logistics and transport sector, the emissions generated by the related consumption of energy accounts for about 2.8 billion tonnes of CO_{2eq} represent about 5.5% of the total GHGs emissions (Fichtinger et al., 2015). Therefore, the environmentally sustainable management of logistic activities became an essential element of business strategy and competitive advantage (Dey et al., 2011).

In recent years, most of the research concerning environmental impact of logistics focused on the GHGs emissions associated with transport activities. There is a growing body of literature focusing on inventory management policies.

According to (Amjed, 2013), each area of research is able to ensure a significant contribution for logistic sustainability improvement. As far as the MHE area is concerned, in order to minimize emissions due to picking activities, a fundamental role is played by the optimal equipment selection.

According to (Johnson, 2008) '*the carbon footprints of electric and LPG fork-lifts are, in principle, about equal, while in actual practice, LPG footprint is smaller than that of electricity*'. On the other hand, (Toyota, 2002) claims that the carbon footprint of a LPG forklift is about twice that of an electric forklift. Therefore the question is: 'what is the forklift engine, available on the market that ensures the minimal carbon footprint for the inbound material handling activities?' It is an issue of incredible concern since mainly powered LPG or electric forklift carries out earth moving in waste treatment. Thus, in the general optimization perspective that will be addressed in the next chapter, this aspect is also addressed to select the best equipment.

3.3.2 Minimize the carbon footprint of inbound logistic activities: comparison of electric and LPG forklifts

A model to select the MHE with the lowest impact in terms of Carbon Footprint (CF) has been developed. Two main classes of MHE have been considered in the model: forklifts powered by fossil fuel and by electricity. Basically, the CF of inbound logistic activities depends on forklift energy consumption and on the time required to complete a process. Process simplifications are needed given the enormous variability that characterizes the actual processes. It is believed that simplification does not compromise the final validity, as what it is sought is a rule of thumb able to orient decision. The material handling process considered in the model consists of three main steps:

1. the unloaded forklift leaves the loading/unloading area (A_{LU}) of the plant and reaches the loaded area (SA) whose access point is located in the middle of front side; a constant carrying speed has been assumed;
2. the forklift stops at SA and picks the number of waste bales (items from now over) in order to both maximize the utilization ratio and to minimize the number of movements and travels required;
3. the loaded forklift leaves the SA and reaches the loading/unloading area (A_{LU}) of the plant. In this phase, the travel speed of the forklift depends on the weight of the load carried up and on the power source of the forklift. In any case, the travel speed cannot exceed the 'safe speed' suggested by occupational safety guidelines for Powered Industrial Trucks (ANSI, 2004) consistently with the truck type, the carried load, the operating surface conditions, as well as other safety issues.

Energy (*E*) and time (*t*) required by the forklift for picking *Q* items are strongly related to the number and features of the items handled to the distance between A_{LU} and SA as well as to the loading capacity of the forklift. Consistently, the CF of material handling activities is evaluated by means of equations (2) for both fuel engine equipped forklifts and electrical powered forklifts:

$$CF = EHR \cdot t \qquad (2)$$

Where:

- EHR: Emission Hourly Rate [$kgCO_2/h$];
- t: total cycle time [h].

The EHR can be calculated by means of equations (3) and (4) for fuel engine equipped forklifts and for electrical powered forklifts, respectively:

$$EHR_{FUEL} = FEF \cdot FCHR \qquad (3)$$

$$EHR_{EL} = \frac{1}{\eta} EEF \cdot ECHR \qquad (4)$$

Where:

- FEF: Fuel Emission Factor [kgCO_2/ kWh];
- FCHR: average Fuel Consumption Hourly Rate [kWh/h];
- EEF : Electricity Emission Factor [kgCO_2/kWh];
- ECHR : average electric Energy Consumption Hourly Rate [kWh /h];
- η: overall efficiency of the electric energy transfer process from the production origin to the battery energy storage (product of the efficiencies of all the involved electric equipment and of the electrochemical charging efficiency of the battery);

The total time (t) considered in the model can be defined as the product of the average cycle time (t_c) and the cycles number (N). The average cycle time $(\bar{t}_C)$ consists of the roundtrip translation time and of the lift time. The cycles number (N) represents the number of roundtrips required to complete the process. Under the hypothesis that all the items in the storage are identical (same weight W and dimensions) and stackable, it is possible to define the Batch Size (BS) of the forklift as the maximum number of transportable units, in order to maximize its utilization. The BS can be calculated as the lower integer of the ratio between the rated Load Capacity (LC) of the forklift and the weight (W) of an item. Consequently, the cycles number (N). is calculated as the upper integer of the ratio between the storage capacity (Q) and the batch size (BS). The total time (t) is at last expressed by equation (5).

$$t = 2\left(\frac{d}{s_t} + \frac{h}{s_l}\right)\left\lceil\frac{Q}{BS}\right\rceil \qquad (5)$$

Where:

- d: average distance travelled in a cycle [m];
- s_t: average translation speed [km/h];
- h: average lifting height [m];
- s_l: average lift speed [km/h];
- BS: forklift batch size. $BS = \left\lfloor\frac{LC}{W}\right\rfloor$ and, consistently, utilization $U = \frac{BS \cdot W}{LC}$, in which LC is the rated load capacity of the forklift truck and W is the weight of an item.

The average distance travelled ‘d’ includes the distance travelled from A_{LU} and SA and the distance travelled in the storage area for picking items. The latter is evaluated according to standard criteria pertaining the minimal distance traveled in condition of equiprobable access to the stocked items. Considering the front side (U) end the depth (V) of SA, the average distance travelled is d=U/4+V/2.

Introduced the subscripts also for the term t and for its components, the CF comparison condition to identify the best MHE is expressed by inequality (6):

$$EHR_{FUEL} \cdot t_{FUEL} - EHR_{EL} \cdot t_{EL} > 0 \qquad (6)$$

A difference greater than zero indicates a preference for the electric forklift. The environmental preference condition can be rewritten as in inequality (7).

$$\frac{EHR_{FUEL}}{EHR_{EL}} > \frac{\left(\frac{d}{s_{t\,EL}} + \frac{h}{s_{l\,EL}}\right)\left\lceil\frac{Q}{BS_{EL}}\right\rceil}{\left(\frac{d}{s_{t\,FUEL}} + \frac{h}{s_{l\,FUEL}}\right)\left\lceil\frac{Q}{BS_{FUEL}}\right\rceil} \qquad (7)$$

For an average travelled distance much greater than the average lifting height, the lift time for both the types of forklift can be neglected. In general, the product of the two terms (h/d) and (s_t/s_l) should be evaluated for both types of forklift, but, in most practical cases, it can be assumed negligible ($h/d \cdot s_t/s_l <<1$). Under this hypothesis, the CF preference condition can be expressed as in inequality (8), in which it is a function of the forklift utilization.

$$\frac{EHR_{FUEL}}{EHR_{EL}} > \frac{s_{t\,FUEL}}{s_{t\,EL}} \frac{\left\lceil \frac{Q}{BS_{EL}} \right\rceil}{\left\lceil \frac{Q}{BS_{FUEL}} \right\rceil} \qquad (8)$$

The model is validated by means of a tool allowing to evaluate the energy and the time required by the forklift in each phase of the material handling cycle: empty travel, item picking and transport, item unloading. The tool is based on VBA macro and simulation software: '*FlexSim Simulator Software*® - *express for free version* (download by: https://www.flexsim.com/free-trial/). VBA macro gets data (times required for Material Handling Cycle) from simulation software, and calculates the related Carbon Footprint according to (2).

The order-picking strategy considered for the warehouse management is based on a picker-to-parts system employing workers and counterbalance forklifts. In the following, the assumptions adopted:

- no priority rules are establish among items;
- number of items to be handled, within a given time horizon, is given;
- an item consist of a single product or a batch of products;
- items stocked in the warehouse are of prismatic form and are characterized by the same sizes (d_x, d_y, and d_z) and weight (w);
- stackable units storage configuration is adopted;
- items are stocked in stockpiles of the same height each stockpile does not exceed 4 [m];

- a storage configuration is univocally identified by the numbers (n_x, n_y, n_z), of items stored along the x, y and z-axis, respectively.
- Q is the storage capacity of the warehouse: $Q = n_x n_y n_z$;
- times of the transient phases (acceleration and deceleration of the forklift) (Chao-Hsien Pan, Ming-Hun & Wen-Linag, 2014) and forklift waiting times are negligible in the cycle time;
- warehouse layout is of a rectangular type (Figure 9)with a storage area (SA) and a single loading/unloading area (A_{LU});
- each stockpile is accessed by a front storage area (F_{SA}) due to limited aisles width;
- the distance between the loading/unloading area (A_{LU}) of the warehouse and the storage area (SA) is given.

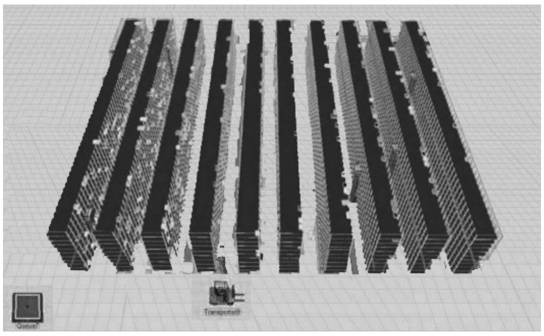


Figure 9- Layout of the warehouse (*FlexSim Simulation software®*)

3.3.3 Numerical simulation of material handling

In order to evaluate the tool effectiveness, the model has been applied to a full scale numerical case. Two counter-balance forklifts equipped with LPG and electric engine are considered.

The data employed for the environmental preference evaluation are listed in Table 4. In detail, the data specified for the LPG powered forklift are the FEF and the FCHR for the considered truck model (equation 3). For the electric powered forklift (equation 4), the ECHR is specific to the truck model and the reported EEF is taken from (Eurostat, 2015). This value is derived considering the average mix of production sources of electricity in EU countries. The overall efficieny η of electric energy storage can be assumed equal to 0.85, considering, optimistically, 90% energy efficiency for the battery charging process and around 95% for all the other ancillary equipment.

Table 4- Emission factors of fuels and consumption data of the considered forklifts (IPPC, 2006)

LPG powered forklift	**FEF [kgCO$_2$/kWh]**	**FCHR [kg/h]**	**LCV [kWh /kg]**	**EHR [kgCO$_2$/h]**
	0.227 (*)	6,6 (**)	13.1	19.6
Electric powered forklift	**E$_R$ [kgCO$_2$/kWh]**	**ECHR [kWh /h]**	**η**	4.84
	0.388 (+)	10.6 (**)	0.85	

(*) source: (IPCC, 2006)

(**) source: Technical data sheet (Hyster H6.0-7.0FT and J4.0-5.0XN), based on the VDI 2198 cycle.

(+) source: (Eurostat, 2015)

Forklift characteristic features like load capacity, fork height, translation maximum speed and engine power are listed in Table 5.

The stocked prismatic items stocked are characterized by the following sizes: dx=0.8 [m], dy=1.2 [m], and dz=0.5 [m]. In the following, the plan of the simulations adopted is summarized. For each case, the model, on the basis of the input parameters, allowed to evaluate the CF required for material handling activities, consistently with the adopted assumptions.

Table 5- Technical specifications of the forklifts

Energy source	Load capacity [kg]	Fork height [mm]	Translation speed [km/h]	Average Lifting/Lowering speed [km/h]	Power [kW]	Cost [k€]
LPG	6000	3340	25.0	1.91	77	≈45
Electric	4000	3300	20.0	1.69	64.4	≈45

By varying the number (Q) and the features (size and weight) of the items to be stocked, as well as the distance between the loading/unloading area and the storage area (A_{LU}-SA), more than 600 numerical cases have been simulated. For each case considered, the model identified the MHE minimizing the CF of the material handling activities. As an example, results obtained in case of A_{LU}-SA=20 [m], three values of Q and three different items (differing by weight) are shown in Table 6.

Table 6- Input parameters for different numerical simulation

ID	Q [units]	Weight [kg/units]	n_x [units]	n_y [units]	n_z [units]
#01	1500	2000	25	15	4
#02	1500	3000	25	15	4
#03	1500	3500	25	15	4
#04	6500	2000	50	26	5
#05	6500	3000	50	26	5
#06	6500	3500	50	26	5
#07	16000	2000	64	50	5
#08	16000	3000	64	50	5
#09	16000	3500	64	50	5

In the case study analyzed, the ratio 'h/d' is also evaluated. The previous illustrated condition (Section 3.3.2), in order to simplify expression (7) into inequality (8), can be rewritten as:

$$\frac{d}{h} \gg \frac{s_t}{s_l} \quad (9)$$

The ratios between the translation speed and the lifting speed are equal to 13 and to 12, for the LPG forklift and for the electric forklift, respectively; therefore, the more stringent condition is set by the value 13. Considering that, at most, stockpiles are constituted by 5 stacked units (see Table 3) and considering the item height, the average lift height of the process is around 1 [m]. In order to satisfy condition (7), the average cycle travelled distance has to be much greater than 13 [m]. This condition is respected since the distance travelled from A_{LU} to SA is yet 20 [m] and distances travelled inside the SA have to be added to it, when considering the average cycle travel. Consequently, the lift time can be neglected. As above mentioned, the travel speed of the forklift depends on the weight of the load carried up. In the simulation software, the variation of the transfer speed with the load carried up by the forklift is considered by means of the following relation:

$$\frac{s_t}{s_{t\,MAX}} = k = f(U) \quad (10)$$

The characteristic ratio '*k*' is a function of the forklift utilization. High values of the forklift utilization imply low values of *k*, since the speed must be reduced for technical and safety problems. Oppositely, low values of the forklift utilization imply high values of '*k*'. Consistently, the enviromental preference condition (8) can be customized as in equation (11).

$$\frac{EHR_{FUEL}}{EHR_{EL}} > \frac{s_{t\,FUEL\,MAX}\ k_{FUEL}\,(U_{FUEL})}{s_{t\,EL\,MAX}k_{EL}\,(U_{EL})} \frac{\left\lceil \frac{Q\cdot W}{U_{EL}\cdot LC_{EL}} \right\rceil}{\left\lceil \frac{Q\cdot W}{U_{FUEL}\cdot LC_{FUEL}} \right\rceil} \quad (11)$$

It can be assumed a variation of the value k in the following range according to the utilization value.

$$
for \begin{cases} 0 \le U \le 0.25: & 0.9 \le k \le 1 \\ 0.25 < U \le 0.5: & 0.6 \le k < 0.9 \\ 0.5 < U \le 0.75: & 0.4 \le k < 0.6 \\ 0.75 < U \le 1: & 0.2 \le k < 0.4 \end{cases}
$$

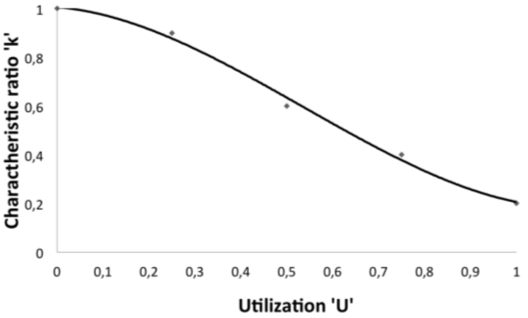


Figure 10- Correlation between translation speed and forklift utilization

3.3.4 Simulation Results

Results and corresponding trends are depicted in Figure 11.

For the storage capacity Q = 1500 items (Figure 11a), the electric forklift performs better for "light" and "medium" weight (W≤3000 [kg]). On the contrary, the LPG forklift performs better than the electric ones for "heavy" (W>3000 [kg]) loads. This is due to the different forklifts load capacity. Indeed, the load capacity strongly affects the BS and forklift the utilization. In turn, the latter influences the speed employed and consequently the time required for the process.

In Figure 11b, results obtained in the case of items with a 'low' weight (equal to 2000 [kg]) are depicted. Coherently, the electric forklift has a lower CF than the LPG one. Considering a weight equal to 2000 [kg], the utilizations of the two forklift are the same and equal to 1. Unitary utilization means transit speed considerably lower than the maximum speed. Specifically, the translation speed of the electric forklift is lower than that of of LPG forklift. Consistently, the electric forklift time is higher. However, the time increase is compensated by the lower value of EHR, since the EHR is equal to 4.84 [kgCO_2/h] for the electric forklift and 19.6 [kgCO_2/h] for the LPG forklift.

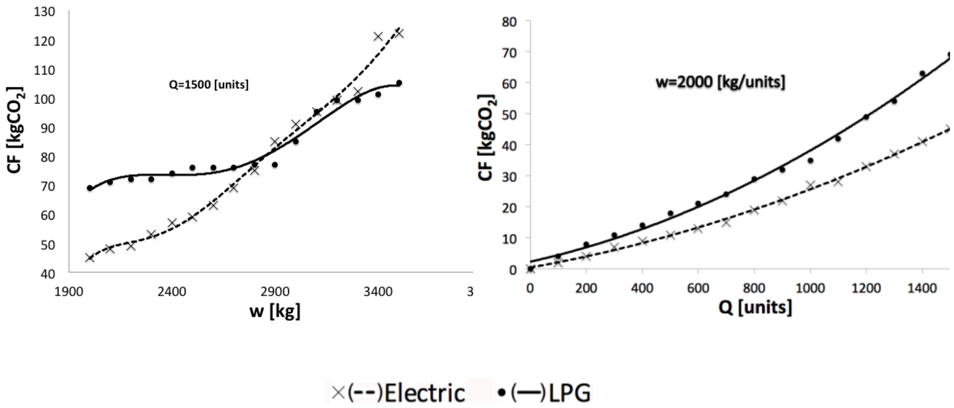


Figure 11- (a)CF vs. Weight value of items in case of 1500 units, (b)CF vs. Q values in case of item Weight equal to 2000 [kg].

In the simulation tests carried out, the following main conclusions are obtained:

- the electric powered forklift allows better performance (lower CF) than the LPG powered forklift for low-mid weight of the units (see Figure 11);
- CF is almost the same for higher values of Q (greater warehouse capacity).

Summarizing, it is not possible to find an ‘a priori’ better configuration. The equipment ensuring the minimal environmental impact has to be evaluated for each case.

Consistently with this consideration and considering the average weight handled in waste treatments plants, the LPG forklift is included in the optimization model.

CHAPTER 4

OPTIMIZATION MODEL TO MINIMIZE ENVIRONMENTAL IMPACT OF INTEGRATED WASTE MANAGEMENT SYSTEM

4.1 Introduction

This Chapter addresses RQ4 –RQ5 and pursues RO3- RO4.

As highlighted in Chapter 1, a research gap exists. While the economic aspects have been widely investigated and considered the main drivers for both the choice and the evaluation of alternatives decisions hitherto, environmental and social aspects have long been set aside. The current size problem suffers from this underestimation. Lately, the environmental and the social aspects are gaining more attention.

The natural structure of the problem suggests the formulation of a mixed integer non-linear programming model to minimize GHGs emissions of waste integrated waste management system. The holistic framework proposed in the previous Chapter, is used to shape strategic and operational problems. Indeed, the model allows the collection service design that affects quantity and quality of waste to be treated and recovered. This in turns affects waste treatment and valorisations to optimize environmental performance of the whole system. The model combines typical aspects of systems engineer tool, such as comparison of different waste treatment technologies and typical aspects of waste assessment tool such as the environmental performance.

Although technical and organizational efforts are crucial for better performance of the system, a pivotal role is played by the citizens. Understanding how their behaviour influences the performance of the system is important for aligning actions / investments in this direction amplifying the benefits of the above innovative technologies and solutions.

In section 4.2 the methodological approach followed in the evaluation of GHGs emissions is explained. In Section 4.3 the optimization model is detailed. In Section 4.4, to test the model effectiveness, it has been applied to a full case study. Scenarios analyses differing in the level of separate collection, which is considered ranging from 50 % to 60 %, have been carried out in Section 4.5. Assessment of citizens' participation is exploited in Section 4.6. Final remarks are addresses in Section 4.7.

4.2 GHGs emissions evaluation: methodological approach

The quantification of GHGs emissions includes Kyoto gases emitted by activities of a MIWMS:

- Carbon Dioxide (CO_2)
- Methane (CH_4)
- Nitrogen dioxide (N_2O)

No other gases are considered since their contribution is negligible (Teichmann et al., 2013). The Global Warming Potential (GWP) allows emissions expressed in a common metric i.e. CO_{2eq} units. Over a time period of 100 years, the GWP of CO_2 is unitary while effects on GWP is estimated for CH_4 e N_2O as 21 CO_2unit /CH_4 unit e 310 CO_2unit / N_2O unit.

Following Greenhouse Gas (GHG) Protocol' taxonomy, direct GHG emissions are emissions from sources pertaining to the entity (e.g the city).

Indirect GHG emissions are those that occur outside from sources not owned by the entity but strictly related to activities of the entity.

It is considered the full implications of waste management system by accounting all direct and indirect related emissions. A comprehensive evaluation requires avoided emissions due to green energy and secondary raw materials production to be accounted for. Avoided emissions occur outside the city boundaries: however, they are considered in the evaluation since they provide a net benefit to society.

In the following sections, emissions calculation methods are explained for each waste management options.

4.2.1 Waste collection emissions

Nature and mass flow-rate of gas emissions depend on several factors: speed, payload, style of driving, fuel combusted, type and physical status of vehicle.

However, (IPCC, 2006) guidelines consider for the transport activities, a distance-based approach for estimating CO_{2eq} emissions for each type of vehicle, payload and average speed. Table 16 summarizes distance-based emission factors (Inemar, 2013).

Table 7- Distance-based emission factors

Vehicle type	Payload [m^3]	Average speed [km/h]	Emission factor [kg CO_{2eq}/km]
Mini-compactor	7	10	0.260
Side/Rear load compactor	10	15	0.697

Consistently, CO_{2eq} emissions per time unit [tCO_{2eq}/time unit] can be evaluated as:

$$Em_{transport} = EF_{fb}AD \quad (12)$$

where:

- $Em_{transport}$: transport emissions [kg CO_{2eq}/time unit];
- EF_{db}: distance based emission factor [kg CO_{2eq}/km];
- AD: activity data [km/time unit].

4.2.2 Waste treatment processes emissions

Waste treatments' processes can be categorized in: mechanical treatments, biological treatments, thermo-chemical treatments.

In order to estimate GHG emissions released from different waste management practices, further assumptions are required concerning the carbon contents of different waste fractions treated. Waste composition and treatments account for different amount of Degradable Organic Carbon (DOC) and Fossil Carbon (FC) (IPCC, 2006).

DOC is the portion of organic carbon that is susceptible to biochemical decomposition. Fossil carbon is the carbon bound in inorganic compounds (i.e. fossil fuels). Biogenic CO_2 emissions are defined as CO_2 emissions related to the natural carbon cycle, as well as those resulting from the production, combustion, digestion, decomposition, and processing of biologically based materials (EPA, 2015). According to the convention usually applied, the biogenic CO_2 is neutral in terms of global warming and is not accounted as GHG emission. It is referred to IPCC Guidelines for National Greenhouse Inventory for data about DOC content and fossil carbon fraction for different waste types.

In the following, the CO_{2eq} estimation approach is described.

Mechanical treatments

Mechanical treatments contribute to both direct and indirect GHGs emissions.

The direct emissions relates to fuel consumptions due to combustion engines for waste material handling (e.g front end loaders). IPCC guidelines suggest in this case the adoption of a fuel-based approach.

Consistently, CO_{2eq} emissions per time unit [tCO_{2eq}/time unit] can be evaluated as:

$$Em_{transport} = EF_{fb} \cdot AD \cdot W \quad (13)$$

where:

- $Em_{transport}$: transport emissions [kg CO_{2eq}/time unit];
- EF_{fb}: fuel based emission factor [kg CO_{2eq}/l fuel];
- AD: activity data [$l_{\ fuel}$/$kg_{\ waste}$];
- W: waste treated [$kg_{\ waste}$/ time unit].

The emissions factor EF_{fb} is based on the fuel's heat content and on the fraction of oxidized carbon in the fuel. According to IPCC guidelines, the full oxidation of fuel is assumed. The fuel based emission factor EF_{fb} can be evaluated as in (14).

$$Em_{fb} = LHV_{fuel} \cdot EF_{fuel \cdot} \gamma_{fuel} \quad (14)$$

where:

- EF_{fb}: fuel based emission factor [kg CO_{2eq}/l fuel]
- LHV_{fuel}: fuel lower calorific value [kWh/kg]
- γ_{fuel} : fuel density [kg/l]

  EF_{fuel}: fuel emission factor [$kgCO_{2eq}$/kWh]

The indirect GHGs emissions relate to electricity consumption of treatments equipment. Electricity emission factor is evaluated as it is suggested by the Baseline Emission Inventory (BEI).

The contribution of National/European emission factor, of local electricity production and, finally of purchases of certified green electricity by local authority are taken into account in the evaluation. The estimated emission factor is 0,267 [t_{co2eq}/ MWh]. Consistently, electricity CO_{2eq} emissions per time unit [tCO_{2eq}/time unit] can be evaluated as in (15).

$$Em_{electricity} = EF_{el} \cdot AD \cdot W \quad (15)$$

where:

- $Em_{electricity}$: electricity emissions [t_{co2eq}/ time unit]
- EF_{el}: electricity emission factor [t_{co2eq}/ MWh]
- AD: activity data [MWh/ kg_{waste}]
- W: waste treated [kg_{waste}/ time unit]

Biological treatments

In biological treatments both electricity-based and fuel-based estimation hold. Furthermore, in the composting process organic carbon in the biomass is oxidized and released as CO_2. Since these are "biogenic" CO_2, they are global warming neutral. When anaerobic conditions temporarily occur in the composited mass, CH_4 and N_2O are released as well. Nevertheless, under well-controlled process conditions these emissions are negligible (Teichmann and Schempp, 2013).

Combustion

The combustion of municipal waste involves the generation of climate-relevant emissions. Emissions are mainly constituted by CO_2 as well as N_2O with other gases that are not considered in the analysis. Except under particular conditions, methane is not to be regarded as climate relevant in waste combustion. Undoubtedly, CO_2 constitutes the chief climate-relevant emission and is considerably higher (Johnke, 2006).

The fossil carbon contents from for example oil products such as plastics, are emitted and accounted for during combustion processes. Despite, combustion emissions from paper, wood and biowaste are not accounted for due to biogenic origin (EC, 2011). It is a *good practice* to calculate CO_2 emissions considering each component in waste combusted as in (16).

$$Em_{comb} = W_{comb} \sum_j (WF_j dm_j CF_j FCF_j OF_j)\, {}^{44}\!/_{12} \quad (16)$$

where:

- Em_{comb}: combustion emissions [t_{co2eq}/ time unit];
- W_{comb}: waste as wet weight incinerated [t/ time unit];
- j: waste fraction incinerated;
- WF_j: fraction of waste j in W_{comb};
- $dm_{j:}$ dry matter content;
- CF_j: fraction of carbon in dry matter;
- FCF_j: fraction of fossil carbon in the component j;
- OF_j: oxidation factor;
- 44/12 : conversion factor from C to CO_2.

These issues are applied to the environmental assessment of RDF and flameless combustion. Emissions of any auxiliary fuel used in the combustion (i.e. during the flameless combustion), will be evaluated according to the rules set out in previous Section about the mobile combustion.

Landfill

For consistency with IPCC methodology, all landfill GHGs emissions are assessed as though they take place instantaneously. DOC is one of the main parameters affecting CH_4 emissions from solid waste disposal (IPCC, 2006). Methane often represents more than 50% of the landfill gas. The other part is constituted by CO_2 [EPA] and is considered mainly carbon neutral. Thus, the type of waste disposed and in turn the amount of DOC degraded under anaerobic conditions greatly influence the amount of methane emitted.

4.2.3 Waste valorisation processes emissions

Avoided emissions of greenhouse gases originate from both the substitution of energy and of materials derived from waste as alternative source. Materials recovery from waste and subsequent recycling leads to avoided GHG emissions compared to a situation where raw materials are used. Avoided emissions are calculated as difference between emissions associated with the production of a product from virgin raw materials and emissions associated with the production of the same from secondary raw materials.
Avoided emissions per unit of recovered waste are listed in Table 8.

Electricity produced from biogas, syngas and downstream flameless and RDF combustion may be used for on-site needs. Surplus electricity is exported to the grid and replaces electricity produced from conventional sources.

Table 8- Avoided emissions per ton of recovered waste (EPA)

Waste fraction	**Avoided emission [tCO_2/t_{waste}]**
Paper, cardboard	-0,61
Plastics	-1,45
Ferrous and al.cans	-1,50
Glass	-0,26
Textile	-3,18
Wood	-2,47
Bulky waste	-1,40

In CHP, also heat from the gas combustion process can be recovered and sold and thus lead to avoided GHG emissions by displacing other sources of heat generation.

In Table 9, an overview of GHGs emissions accounted for in the analysis is provided.

The evaluation does not take into account:
- non-greenhouse gas impacts of waste management options.
- emissions from plant construction.

Table 9- Overview of GHGs emissions accounted in the optimization model

PHASE	**DIRECT EMISSION**	**INDIRECT EMISSION**	**AVOIDED EMISSION**
Collection	CO_2, CH_4, N_2O released from fuel consumed in waste collection. (*IPCC distance-based approach)*		
Dry-recyclable treatment	CO_2, CH_4, N_2O released from fuel consumed in internal handling. (*IPCC fuel-based approach)*	CO_2 from electricity grid consumption	Avoided emissions from material recovery and subsequent recycling processes.
Biological treatment (composting and anaerobic digestion)	CO_2, CH_4, N_2O released from fuel consumed in internal handling. (*IPCC fuel-based approach)*	CO_2 from electricity grid consumption	Avoided emissions for the fertilizer and peat replacement by compost. Energy generation emissions avoided through energy recovery from

	CO_2 released in aerobic condition not accounted for since biogenic) CH_4, N_2O released in anaerobic processes		biogas
Mechanical-biological treatment	CO_2, CH_4, N_2O released from fuel consumed in internal handling. *(IPCC fuel-based approach)*	CO_2 from electricity grid consumption	
Recovery unrecycled material	CO_2, CH_4, N_2O released from fuel consumed in internal handling. *(IPCC fuel-based approach)*	CO_2 from electricity grid consumption	Avoided emissions from un-recycled material recovery and subsequent recycling processes.
Gasification		CO_2 from electricity grid consumption	Energy generation emissions avoided through energy recovery from syngas
Refuse derived fuel **Flameless combustion**	CO_2 released during waste combustion. Only the fossil carbon is considered. CO_2 released from the auxiliary fuels used during combustion.		Energy generation emissions avoided through energy recovery from flameless combustion and RDF Emissions saved through carbon storage for the flameless combustion.
Landfill	CH_4 emitted in the landfill gas		

4.3 Minimize GHGs emissions: a Mixed Integer Non Linear Programming Model

A Mixed Integer Non Linear Programming (MINLP) model is developed to support decision makers in finding out the MIWMS with the lowest environmental impact. The model works at different planning levels simultaneously. As highlighted in Chapter 3, operative decision variables relate collection service design: waste grouping, waste collection systems, waste collection frequencies. Strategic decision variables relate treatment technologies: waste fraction to be addressed to primary and secondary treatment processes.

Decision variables pertain a municipal authority committed in the management of the overall MIWMS. Consistently, paper mills, glassmakers and the others facilities for the recovery of recycled materials are not considered in the analysis. To be thorough, the contributions are included by avoided emissions originating by recovery materials.

The indexes and the parameters are listed in Table 10. The model aims at jointly design and plan a MIWMS minimizing the net emissions by means of the following decision variables:

- $Y_{i,k}$: boolean variable to infer if the i-th grouping system is adopted for the k-th waste fraction. $Y_{i,j}$ is defined in the set $N=\{0;1\}$
- $N_{j,i,k}$: number of domestic users served by the j-th collection system and the i-th grouping for each k-th fraction. $N_{j,i,k}$ is defined in the set *N*.
- $C_{j,i,k}$: number of commercial users served by the j-th collection system and the i-th grouping for each k-th fraction. $C_{j,i,k}$ is defined in the set *N*.
- $w_{j,i,k}$: weekly collection frequency for the k-th waste fraction collected by the j-th collection system and the i-th grouping system. $w_{j,i,k}$ is defined in the set *N*.

- $F_{k,s}$: fraction of the k-th waste addresses to the s-th primary treatment. $F_{k,s}$ is defined in the set *Q*.
- $F_{k,s,v}$: fraction of the k-th waste treated in the s-th primary treatment addresses to the v-th secondary treatment. $F_{k,s,v}$ is defined in the set *Q*.

Table 10- List of indexes and parameters in the optimization model

Symbol	Description
k	Waste fractions k = 1 organic; k = 2 glass; k=3 paper; k = 4: plastics, metal cans; k=5 cardboard; k=6 wood; k=7 textile; k=8 un-recyclable; k=9 others.
i	Grouping Systems i =1 mono material; i = 2 multi stream.
j	Collection Systems j=1door-to-door; j=2 aggregate; j=3 proximity; j=4 street
s	Primary treatments s=1sorting; s=2 selection s=3 pre-treatment anaerobic digestion; s=4 anaerobic digestion s=5 post-treatment digestion s=6 composting s=7 MBT s=8 bio-stabilization; s=9 landfill.
v	Secondary treatment of MSIWMS v=1ReMat (Recovery Material un-recycled), v=2 RDF; v=3 gasification; v=4 pre-treatment flameless; v=5 flameless combustion; v=6 flameless capture.
g_c	Production per capita of urban waste [ton/y·ab]
G	Total amount waste produced [ton/y]
H	Number of work-hours per day [h]
W	Number of weeks in the observation period [#]
g_k	Fraction of the k-th type of G è [%]
v_j	Average speed of the transport mean adopted by the j-th collection system [km/h]
b_j	Bin load capacity [#users]
P_{ji}	Productivity for i-th stream grouping and the j-th collection system [unit/shift]
η_{kji}	Collection efficiency of the k-th material collected by the j-th waste collection system and the i-th waste stream grouping [%];
N_T	Total number of domestic users [#]
O_{MBT}	Organic not-recycled flow after MBT [%]
e_{ks}	Efficiency of s-th stage for the k-th waste fraction [%].
e_{kv}	Efficiency of v-th stage for the k-th waste fraction [%].

AD_s	Activity Data in the s-th stage [kWh/ton]
AD_v	Activity Data in the v-th stage [kWh/ton]
MC_s	Mass Capacity of plant in the s-th stage [ton/y]
MC_v	Mass Capacity of plant in the v-th stage [ton/y]
EF_{el}	Electricity emission factor [tonCO$_{2eq}$/kWh]
EF_{ji}	Emission factor of the transport mean to collect waste fraction according to the i-th grouping and the j-th collection system [tonCO$_{2eq}$/km] (distance-based approach)
EF_{fuel}	Fuel emission factor [tonCO$_{2eq}$/t$_{fuel}$] (fuel-based approach)
EF_l	Emission factor for disposal waste fraction [tonCO$_{2eq}$/t]
E_k	Energy from recovery of waste (biogas, syngas, RDF e flameless combustion) [kWh/y]
A_k	Avoided emission from recovery and prevented disposal of the k-th recycled materials and compost [tonCO$_{2eq}$/t]

It is defines the index k=9 to indicate the waste flow that includes recyclable waste not-intercepted during the collection phase (from k= 1to k=7). This flow will be addressed to MBT.

Since the s-th stage is strictly dependent on k-th fraction, it is defines S_k the set of the s-th stages available for the k-th waste fraction. Once defined the k-th fraction, the set is univocally identified. The variables $F_{s,k}$ will assume value only in the respective definition set.

Posed S the set of all stages of MIWMS:

$$S_1 = \{s \in S: s \geq 3 \ \wedge s \leq 6\}$$

$$S_2 = S_3 = S_4 = \{s \in S: s \leq 2\}$$

$$S_9 = \{s \in S: s \geq 7\}$$

Likewise, it is defines V_s the set of the v-th stages available after the s-th stages for the k-th waste fraction. The variables $F_{v,s,k}$ will assume value only in the respective definition set.

Posed V the set of all valorisation treatment of MIWMS:

V$_7$ =$\{v \in V: v \leq 3\}$

V$_8$ =$\{v \in V: v \leq 4\}$

The objective function is defined as the algebraic sum of the MSIWMS phases contributions as in (17):

$$F.O = Min\,(Em_{collection} + Em_{dryTreat} + Em_{an.digest} + Em_{compost} + Em_{MBT} + Em_{landfill} + Em_{Rec.mat.sorting} + Em_{RDF} + Em_{gasification} + Em_{flameless} + Em_{en.recovery} + Em_{mat.recovery})$$

Hereinafter, each component of the objective function is detailed.

$$Em_{collection} = \sum\nolimits_i \sum\nolimits_j \sum\nolimits_k (EF_{j,i}\, Hv_j Ww_{j,i,k} Y_{i,k}\, {}^{N_{j,i,k}}\!/_{b_j\, P_{j,i}}) + \sum\nolimits_i \sum\nolimits_j \sum\nolimits_k (EF_{j,i}\, Hv_j Ww_{i,i,k} Y_{i,k}\, {}^{C_{i,i,k}}\!/_{b_j\, P_{j,i}}) \quad (18)$$

$$Em_{dryTreat} = \sum_{s=1}^{2} \sum_{k=2}^{4} \left(F_{k,s} X'_k \prod_{s}^{s-1} e_{k,s-1} AD_s EF_{el} \right) + \sum_{s=1}^{2} \sum_{k=2}^{4} \left(F_{k,s} X'_k \prod_{s}^{s-1} e_{k,s-1} AD_s EF_{fuel} \right) \quad (19)$$

$$Em_{an.digest} = \sum_{s=3}^{4} \left(F_{k,s} X'_k e_{k,s} AD_s EF_{el} \right) \quad (20)$$

$$Em_{compost} = F_{k,s} X'_k AD_s EF_{el} \quad (21)$$

$$Em_{MBT} = F_{k,s}X_k'AD_sEF_{el} + F_{k,s}X_k'O_{MBT}AD_sEF_{el} \tag{22}$$

$$Em_{landfill} = \sum_{s=1}^{2}\sum_{k=2}^{4} X_k'\left(1-e_{k,s}\right)EF_l +$$

$$+\textstyle\sum_{s=3}^{6} X_k'\left(1-e_{k,s}\right)EF_l + F_{k,s}X_k'O_{MBT}e_{k,s}EF_l + F_{k,s,v}X_k'O_{MBT}e_{k,v}EF_l \tag{7}$$

$$Em_{Rec.mat.sorting} = F_{k,s,v}\,(1-O_{MBT})X_k'AD_vEF_{el} \tag{23}$$

$$Em_{RDF} = F_{k,s,v}\,(1-O_{MBT})X_k'AD_vEF_{el}$$

$$+ F_{k,s,v}\,(1-O_{MBT})X_k'e_{k,v}EF_{com.RDF} \tag{24}$$

$$Em_{gasificat} = F_{k,s,v}\,(1-O_{MBT})X_k'AD_vEF_{el} \tag{25}$$

$$Em_{flamelesscomb} = F_{k,s,v}\,X_k'O_{MBT}AD_vEF_{el} + F_{k,s,v}\,X_k'O_{MBT}EF_{flamelesscomb}$$

$$+ P_{auxiliaryfuels}EF_{fuel} \tag{26}$$

$$Em_{en.recovery} = E_kEF_{el} \tag{27}$$

$$Em_{mat.recovery} = \sum_{k=1}^{4}\left(X_k'\prod_{s=1}^{2}e_{k,s}A_k\right)$$

$$+ F_{k,s,v}(1-O_{MBT})\,X_k'e_{k,v}A_k \tag{28}$$

With reference to notation in Table 10, is set:

$X_k = g_cMg_kw_{j,i,k}Y_{i,k}N_{jik}$ and $C_k = Gg_k$

Consistently, it is defined:

$$X_k' = X_k + C_k$$

To solve the optimization model the Generalized Reduced Gradient is used.

4.3.1 Model constraints

The objective function is subject to different type of constraints.
Operative constraints include technical-organizational constraints, service demand constraints as well as normative constraints.

- *Technical-organizational*

$$\sum_i Y_{i,k} = 1 \; \forall k \tag{29}$$

$$Y_{i,3} = Y_{i,4} \tag{30}$$

$$N_{j,2,3} = N_{j,2,4} \;\; \forall j \tag{31}$$

Only one waste stream grouping system is admitted for each k-th waste fraction (29). Logistic opportunities suggest, the adoption of the same i-th waste grouping system for both paper, plastics, and metal cans (30). When a MuMG system is adopted for the dry recyclable fraction, the number of users served by the j-th waste collection must be equal for that fractions(31).

- *Service demand*

$$\sum_i \sum_j Y_{i,k} N_{j,i,k} = N_T \;\; \forall k \tag{32}$$

$$N_{j,i,k} \leq N_{jMAX} \;\; \forall i, j, k \tag{33}$$

$$N_{j,i,k} \geq N_{jMIN} \;\; \forall i, j, k \tag{34}$$

The sum of users served by the j-th collection system and the i-th waste stream grouping system is equal to the total number of the users (N_T) for each k-th waste fraction (32). Collection systems are strictly dependent on urban configuration (historical vs. suburbs areas, street width, population density), as described in Section 3.2.1.2. The number of users served by the i-th waste grouping and the j-th collection system must comply with upper and lower limits depending on the urban features for the k-th fraction (33),(34).

- *Normative*

$$w_{j,i,kMIN} \leq w_{j,i,k} \leq w_{j,i,kMAX} \qquad \forall i,j,k \tag{35}$$

$$\sum_j \sum_i \sum_k \left(g_c M g_k w_{j,i,k} Y_{i,k} N_{j,i,k} \eta_{j,i,k}\right) + \left(G g_k \eta_{j,i,k}\right) \geq SC_{MIN} G \tag{36}$$

Constraint (35) allows a variation of the weekly frequency of collection in a defined set of frequency values according to practical and official waste management guidelines as well as local regulations. The achievement of a minimum level of separate collection (SC_{MIN}) is ensured by constraint (36).

Strategic constraints include resource capacity constraints, treatment demand constraints as well as normative constraints.

- *Resource capacity*

$$X'_k \leq MC_s \quad \forall k,s \tag{37}$$

$$X'_k e_{k,s} \leq MC_v \quad \forall k,s,v \tag{38}$$

The k-th waste flows treated in the s-th primary treatment must comply with the s-th plant capacity (37). The same line of reasoning is applied for the v-th plant constraint (38).

- *Normative*

$$F_{k,s,v} \leq Law_{lim} \tag{39}$$

The fraction of dry materials from MBT addressed to Recovery Materials (ReMat) Plant has to comply with the limits of law, if any (39).

- *Treatment demand*

$$\sum_{s} F_{k,s} = 100 \quad \forall k \tag{40}$$

$$\sum_{v} F_{k,s,v} = 100 \quad \forall k \tag{41}$$

While respecting the primary treatment available for each k-th waste fraction, the total amount of waste collected has to be treated in the s-th primary treatment as evident in constraint (40). The same line of reasoning is applied for secondary treatments (41).

The above-described constraints have a general nature. Specific constraints relating to organizational and technical options designed for the case study will be described in Section 4.4.1.

4.4 Application to a full case study

The case study developed in this section refers to Bari, a middle size city located in Southern Italy, accounting for 147811 families (users from the point of view of the waste management system) each of them having on the average 2.33 members (M). Data relating the number of commercial users are provided by Camera Commercio Industria e Artigianato (CCIA) of Bari. The full list of non-domestic users is provided In Appendix I. The overall municipal waste flow (G) amounts to 176677 t/year (2013 data) and is composed by 76% of household waste and by 24% of municipal commercial waste (C_k). Production per capita (g_c) of household urban waste is 379 [kg/y·ab]. In Figure 12, the composition of waste fractions (g_k) considered in the model is shown.

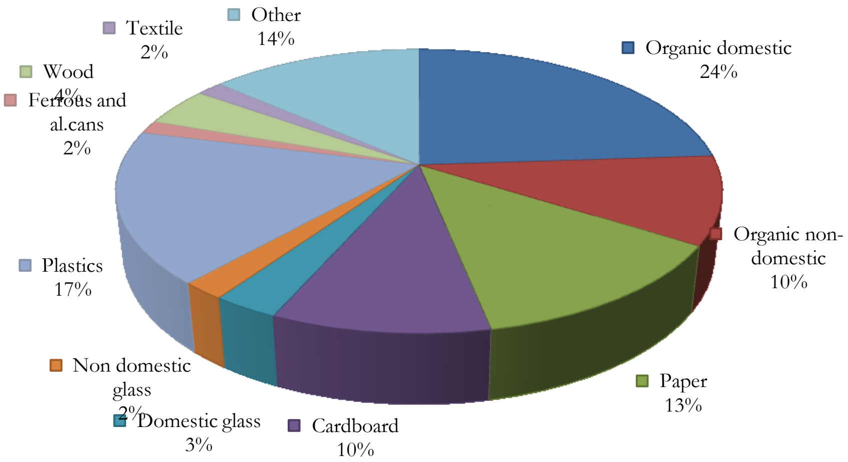


Figure 12- Waste flow composition (%)

4.4.1 Case-study model constraints

In addition to constraints explained in section 4.3.1, the model is subjected to the following case-study model constraints depending on specificities and requirements of the application context.

$$Y_{2,1} = Y_{2,2} = 0 \qquad (42)$$

$$N_{1,1,1} = N_{2,1,2} = 0 \quad \wedge \; N_{3,1,2} \geq 0 \;\wedge\; N_{4,1,2} \geq 0 \qquad (43)$$

$$C_{2,i,k} = C_{3,i,k} = C_{4,i,k} = 0 \qquad (44)$$

$$F_{3,1}F_{6,1} = 0 \qquad (45)$$

$$F_{9,9}F_{4,8,9} = 0 \qquad (46)$$

$$F_{1,7,9} \geq 20 \qquad (47)$$

$$F_{2,7,9}F_{3,7,9} = 0 \qquad (48)$$

For the reasons explained in Section 3.2.1.1 and considering consortia requirements for flows purity, organic and glass fraction are not mixed with each other and with the other waste fraction (42). Due to the low total household glass produced, it is not convenient both the DtD-CS and the A-CS. Consistently, the glass fraction can be collected only by P-CS or S-CS (43). For the non-domestic users, both the service demand and requirements suggest the adoption of a DtD-CS (44). Compost and anaerobic digestion are mutually exclusive for the organic fraction (45). The same applies also for the wet bio-stabilized not recycled fraction address to flameless combustion or to landfill (46). The BURP n.74 of Apulia region issued on 11 June 2014, states that at least the 20% of dry materials from MBT has to be recovered in ReMat plant (47). The dry not recycled fraction is addressed to RDF production and combustion or to gasification (48).

4.4.2 Waste collection data

In this section, data about the waste collection phase are provided. Two classes of collecting transport means have been considered. In Table 7 data about payload, average speed (v_j) and emission factor have been provided.

With a net-duration work-shift of 6-hours, the productivity (P_{ji}) (workload capacity) of workers team, bin load capacity (b_j) and collection efficiency (η_{kji}) for each fraction collected with the i-th grouping and the j-th collection system, are evaluated in Table 11. The collection efficiency represents the percentage of the k-th waste flows produced that is collected with the i-th grouping system and the j-th collection system. It is supposed the flows not intercepted constituting the residual waste flows (k=9).

For the non-domestic fraction (e.g. organic, cardboard, glass) it is supposed a DtD-CS with a high collection efficiency of 90%. Productivity and bin capacity are the same of those listed in Table 11 for the DtD-CS. Moreover, for textile, wood and for un-recycled fraction it is suppose a S-CS. Specifically for textile and for wood fraction collection efficiency is supposed equal to 80%. Productivity and bin capacity are the same of those listed in Table 11 for the S-CS.

Table 11- Productivity (Pji), bin capacity (bj) and collection efficiency (ɳkji) of waste fractions for each grouping and collection system

		MoMG				MuMG			
		DtD-CS	A-CS	P-CS	S-CS	DtD-CS	A-CS	P-CS	S-CS
Organic Domes	Productivity [unit load/shift]	800	200	200	150	--	--	--	--
	Bin Capacity [users]	1	8	15	40	--	--	--	--
	Col. Efficiency [%]	70	70	60	40	--	--	--	--
Glass Domesti	Productivity [unit load/shift]			200	150	--	--	--	--
	Bin Capacity [users]	1	8	15	40	--	--	--	--
	Col. Efficiency [%]	--	--	60	40	--	--	--	--
Paper,plastican al.cans	Productivity [unit load/shift]	800	200	200	150	700	200	200	150
	Bin Capacity [users]	1	8	15	40	1	8	15	40
	Col. Efficiency [%]	65	65	60	40	80	80	70	60

Since the collection systems largely depend on both building features and on urban fabric constraints (see section 3.2.1.2), the lower and the upper number of users that can be served by the different waste collection systems have been evaluated in Table 12.

Table 12- Upper and lower limits of users for the waste collection systems

	DtD-CS	A-CS	P-CS	S-CS
Upper limit (#)	14337	53158	78443	133473
Lower limit (#)	7098	2467	2467	55510

4.4.3 Waste treatments data

In this section, data about the waste treatment plants are provided. Activity data about electricity and fuel consumption for each k-th fraction addressed to the s-th primary treatment are provided in Table 13.

For what concern waste material handling emissions, a LPG forklift is modelled according to conclusions in section 3.4. It is assumed a gas oil low calorific value (LHV) of 11900 [MWh/kg] and a density of 0,85 [kg/l]. Fuel emission factor is 0,227 [tCO_{2eq}/MWh]. Electricity emissions factor is 0,267 [t_{co2eq}/ MWh].

Table 13- Electricity activity data and fuel activity data for each fraction and primary treatment

Primary Treatment '*s*'	**Fraction '*k*'**	**Electricity Activity data [kWh/t]**	**Fuel Activity data [l/t]**
Sorting *(s=1)*	Glass *(k=2)*	12	--
	Paper *(k=3)*	8 50[1]	0,85 3[1]
	Plastics and al.cans *(k=4)*	19	2
	Cardboard *(k=5)*	8	0,85
Selection *(s=2)*	Plastics *(k=4)*	19	2

Pre-treatment anaerobic digestion *(s=3)*	Organic *(k=1)*	16	--
Anaerobic digestion *(s=4)*		30	--
Post-treatment anaerobic digestion *(s=5)*		52	--
Composting *(s=6)*	Organic *(k=1)*	50	--
MBT *(s=7)*	Not recycled waste *(k=9)*	15	--
Bio-stabilization *(s=8)*	Not recycled waste *(k=9)*	48	--

In Table 14, the efficiencies $e_{k,s}$ for different k-th fractions treated by the s-th primary treatments are listed. For the dry recycled fraction (k=2, 3,4,5), that efficiencies represent the percentage of the fraction appropriately sorted and selected. It is supposed the scraps of each dry recycled fraction to be addressed to landfill. For the organic fraction (k=1), the efficiencies represents the percentage of organic flows appropriately treated and addressed to subsequent processes. It is supposed the scraps of organic recycled fraction to be addressed to landfill.

Table 14- Efficiencies $e_{k,s}$ for different k-th fractions treated by the s-th primary treatments

Primary Treatment '*s*'	**Fraction '*k*'**	**Efficiency [%]**
Sorting *(s=1)*	Glass *(k=2)*	97
	Paper *(k=3)*	93
	Plastics and al.cans *(k=4)*	80
	Cardboard	98

	(k=5)	
Selection *(s=2)*	Plastics *(k=4)*	90
Pre-treatment anaerobic digestion *(s=3)*	Organic *(k=1)*	80
Anaerobic digestion *(s=4)*		--
Post-treatment anaerobic digestion *(s=5)*		60
Composting *(s=6)*	Organic *(k=1)*	70

To calculate biogas production, it is considered a percentage of total solid in biogas closed to 25,6%, a percentage of volatile solid closed to 96,5% and specific weight about to 368 Nm3/ton of volatile solid and are provided by (Piano Provinciale (SP) per l'organizzazione del sistema integrato di gestione dei R

These efficiencies allow defining the organic not recycled fraction (O_{MBT}) after MBT. Furthermore, the separation efficiencies allow knowing the waste composition in both the dry not-recycled flow and organic not recycled. It reveals useful to establish combustion emission factors, strictly connected to the waste composition (see Section 4.2.2) for both the dry not-recycled flow addressed to RDF and for the organic not recycled flow addressed to flameless combustion.

Table 15- Separation efficiency of MBT for the not recycled fraction

Fraction	**Efficiency [%]**
Organic	17
Paper	79
Cardboard	99
Plastics	70
Ferrous and al.cans	99

Glass	20
Wood	50
Textile	73
Other	73

The emission factor set for the disposal (s=9) of waste fraction is 0,137 [tCO_{2eq}/t_{waste}].

As mentioned before, biogas is mainly used for CHP application. It is estimated a low calorific value of biogas equal to 5,3 kWh/Nmc. Since biogas CO_2 emissions have a biogenic origin, they are not accounted for. The emissions of CH_4 and of N_2O are respectively 6,75 gCH_4/ ton of burned biogas and 0,0109 gN_2O/ ton of burned biogas. It means 0,145 kg CO_{2eq}/ton of burned biogas.

Electricity activity data for organic and dry not-recycled flow addressed to the v-th secondary treatment are provided in Table 16.

Table 16- Electricity activity data for not-recycled fraction to each secondary treatment

Secondary Treatment 'v'	**Fraction**	**Electricity Activity data [Kwh/t]**
Material Recovery Sorting (v=1)	Dry not-recycled fraction	50
RDF Production (v=2)	Dry not-recycled fraction	40
Gasification (v=3)	Dry not-recycled fraction	Consumption are calculated as percentage of electricity produced by syngas
Pre-treatment flamelss (v=4)	Organic not-recycled fraction	5
Flameless combustion (v=5)	Organic not-recycled fraction	--
Flameless capture (v=6)	Organic not-recycled fraction	--

To catch gasification complexity, the authors uses as sub-model the ones proposed by (Dutta, 2007) based on equilibrium constant for predicting the chemical composition of syngas in a downdraft gasifier. For the model application, the waste fraction composition as well as the waste chemical composition are necessary.

The limited lower calorific value of the bio-stabilized organic not recycled fraction (closed to 1500 [kj/kg]) addressed to the flameless combustion requires the use of auxiliary fuels. The auxiliary fuels considered in the analysis are gas oil and methane. It is supposed a methane lower calorific value of 44700 [kj/kg] and emission factor of 0,231 [tCO_{2eq}/MWh].

Plant capacity (MC) of anaerobic digestion is 60000 [ton/year]. For MBT is set a plan capacity of 146000 [ton/year]. For material recovery sorting and RDF, plant capacity is 60000 [ton/year]. Plant capacities for the others treatments are not reported since concern technological options not yet available in the analysis boundary.

4.5 Results and discussion

The optimization model has been applied to analyse scenarios differing in the level of separated collection (SC-L) which is considered ranging from 50 % to 60 % (36). A sensitivity analysis is performed for intermediate SC-L values.

Emissions values for each phase of the MSIWMS are summarized in Table 17.

Table 17- Optimization results: emissions for each MIWMS phase

		SC -L 50%	**SC-L 52%**	**SC -L 55%**	**SC-L 60%**
Collection	(A)	1116	1113	1067	966

Sorting and Selection	(B)	295	333	375	988
Anaerobic digestion	(C)	1388	1388	1456	1456
MBT	(D)	857	827	773	707
ReMat Treatments	(E)	143	137	129	111
RDF production and combustions	(F)	17540	15892	13939	9130
Flameless combustion	(G)	9284	8918	8469	7506
Disposal	(H)	5160	5230	5335	5567
DIRECT EMISSIONS		*35783*	*33838*	*31543*	*26431*
Secondary raw material	(I)	-55468	-58254	-61415	-69207
Low quality compost and energy from biogas	(L)	-4441	-4441	-4659	-4659
Materials recovery from ReMat	(M)	-14599	-13261	-11678	-7774
Electric Energy from RDF	(N)	-21641	-19887	-17808	-12695
Electric Energy from flameless combustion	(O)	-7908	-7908	-7830	-7807
AVOIDED EMISSIONS		-*104057*	-*103751*	-*103390*	-*102232*
NET TOTAL EMISSIONS		**-68274**	**-69913**	**-71847**	**-75801**

Direct emissions decrease with the increase of SC-L. Direct emissions reduction is mainly due to emissions cuts of RDF production/combustion, flameless combustion and waste collection. In the former case unrecycled waste flow decreases; in the latter case, higher SC-L values are achieved by MuGS collection modality that allows less collection routes.

Avoided emissions decrease with the increase of SC-L. Avoided emissions reduction is mainly due to lower unrecycled waste flow available for both RDF thermal valorisation and material recovery by ReMat plants. Major contribution (from 55 - 70 %) to avoided emissions in any scenario is due to materials recovery by separate collection flows.

In the overall, reduction of avoided emissions is overcome by direct emissions with a net environmental benefit (i.e. the algebraic sum of direct and avoided emissions) that increases with SC. Net total emission increase is mainly due to materials recovery for the production of secondary raw material uptake rate and lower demand uncertainty than the recovered material market.

Operative decision variables about collection service relate to waste grouping systems, collection systems, and collection frequency.

The model suggests the adoption of a MoMG system until the level of separated collection does not exceed 55% of SC. Consistently, a MuMG system is suggested when a SC-L of 60% is pursued. In fact (refer to the first two rows in Table 17), a MuMG system allows on one hand a reduction in collection routes and transport GHGs emissions and, on the other hand, higher sorting treatments unitary energy consumptions and GHGs emissions: the former contribution prevails of the latter one for SC values lower than 60%.

Separate collection systems, which minimize the overall MSIWMS emissions, are analysed and shown in Figure 13. As one can see, the highest emissions are due to the street collection system, mainly for the organic collection, in any of the SC-L scenarios considered.

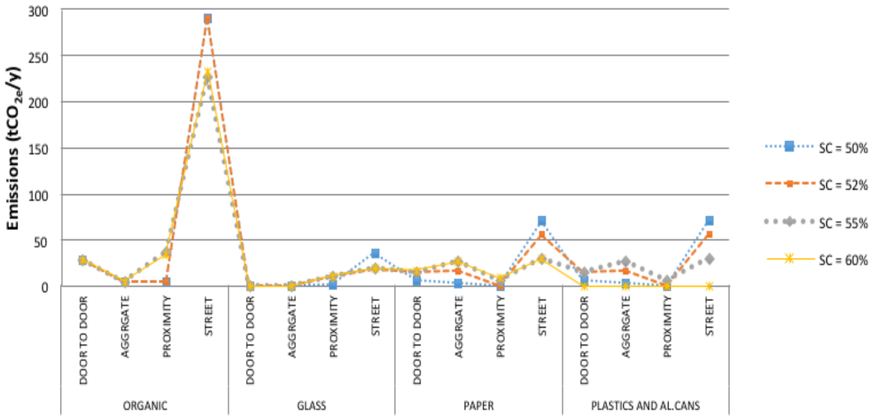


Figure 13- Optimization results: Collection emission for each waste fraction and collection system

Minimum emissions solutions in Figure 13 determine the corresponding optimal number of users by be served by collection systems as per figure 5. As one can see, for the minimum SC-L (50%) scenario, the street collection system reveals as the most adopted (higher number of users). On the contrary, at the highest SC-L (60%) the street option is evaluated as the most adopted only for the organic fraction: different CSs (proximity CS for glass and aggregate CS for dry recycled fractions) are suggested for all the other waste fractions. For the other waste fractions, the S-CS reveals a not environmental compliant option since the high emissions factor of transport means.

A remarkable result can be outlined by comparing results in Figure 14 with the upper and lower limits of the number of users to be served (see Table 12).

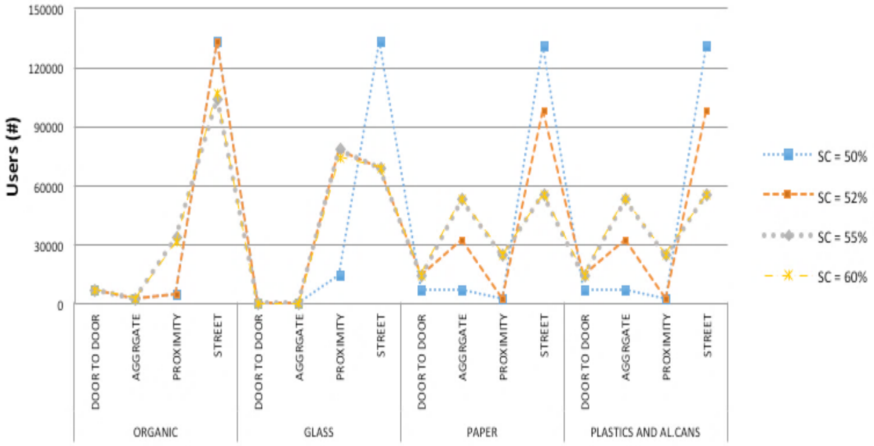


Figure 14- Optimization results: number of users in the different scenarios for each waste fraction and collection system

Differently to the current practice adopted in many municipalities, the number of users served by DtD-CS is kept at the minimum number of users for all the waste fractions in all SC scenarios: the option, currently known as the most expensive, also reveals as the less environmental compliant due to the high work cycles and collection routes required.

Achieving the 55 % or higher values of SC level, requires efficient, intermediate collection systems, like 'aggregate' and ' proximity' systems with a MuMG system for the higher values: environmental benefits due to higher collection efficiency of P-CS and A-CS vs. S-CS counterbalance the negative influence of higher waste collection distance to be covered. A trade-off has to be achieved. The trade-off relates both environmental and technical features of each collection systems. Indeed, the optimal collection configuration is strictly connected with SC targets.

The domestic waste fraction contribution to the SC level is shown in Figure 15 for each scenario analysed. As a general finding, dry recyclable waste fractions mostly contribute to the achievement of higher SC-L and require collection systems with higher collection efficiencies. The rationale of such finding mainly relies on reciprocal influence of both operative and strategic problems. Optimal collection variables stem from collection technical and environmental features of both treatments and valorisation options. Furthermore, the model suggests the adoption of the minimum collection frequency for each waste fraction consistently with the minimum requirements of regional and municipal guidelines.

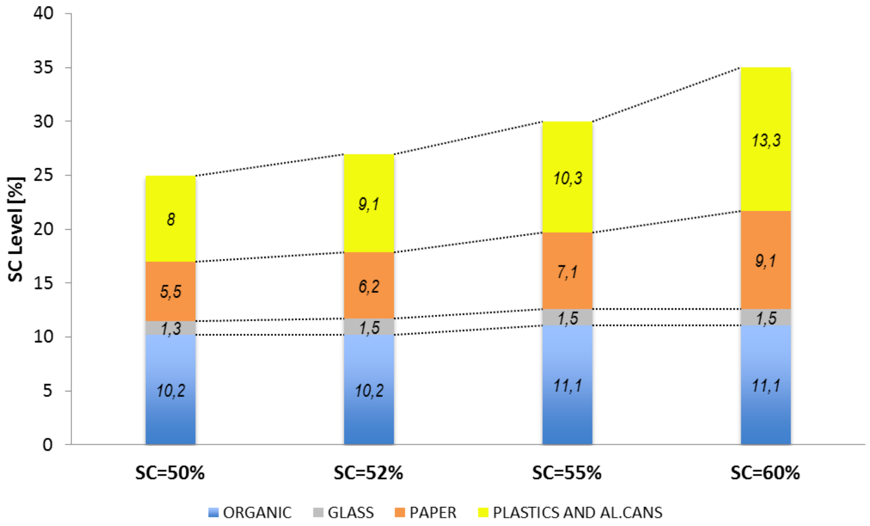


Figure 15- Optimization results: waste fraction contribution to the SC level

Residual flows (k=8 and k=9) does not contribute to the SC-L. For that kind of flow, the solution suggested by the model is the same in all scenario analysed. In detail, the DtD-CS and S-CS reveal as not environmental compliant due to the high distance to be covered and for the higher impact of transport means for S-CS . Consistently the number of users is equal to the minimum level according to limits in Table 12. On the contrary the model completely gluts the P-CS.

The contribution of the non-domestic users to the separate collection level is constant in all the scenarios analysed. The overall contribution of non-domestic waste fractions accounts for 19,6 % (i.e. 9% organic fraction; 8,8% cardboard; 1,8% glass) while the textile and the wood fraction contribute to the separate collection level for the 5%.

Decision variables of treatment options relate the waste fraction addressed to primary treatments and to secondary treatments.

The dry-recyclable fraction separate collected is addresses to sorting and selection plants. Moving from a scenario of SC-L equal to 50% to a scenario of SC equal to 60%, a growing trend in emissions exists due to higher flows to be treated. The use of automatic sorting systems in the last scenario made emissions significantly higher (Table 17). It is assumed that wood and textile fractions are straight sent to consortia for the materials recovery.

In Table 18, the flows of dry recycled fractions in the different scenarios are listed. According to avoided emissions per ton of recovered waste listed in Table 8, the total avoided emissions are evaluated.

Table 18- Optimization results: dry-recycled waste flows [ton/y]

Waste flows [ton/y]	SC=50%	SC=52%	SC=55%	SC=60%
Paper	9053	10216	11592	14986
Cardboard	15552	15552	15552	15552
Glass	5234	5679	5679	5679
Plastics	9413	10623	12054	15584
Ferrous and Al.cans	1021	1152	1307	1689
Textile	2624	2624	2624	2624
Wood	6276	6276	6276	6276

The model suggests the organic fraction from separate collection to be treated in anaerobic digestion plant. Direct emissions from the biogas production plant do not considerably vary (Table 17) since the slight increase of mass flow rate of the organic fraction with the increase of SC level. Consistently, the production of compost and biogas as well as thermal and electrical energy is almost constant as it is shown in Table 19.

Table 19- Optimization results: production of biogas [Nmc/y] and compost [ton/y]

	Biogas [NM^3/y]	**Compost [ton/y]**	**kW_e**	**kW_t**
SC=50%	3166897	10365	797	1469
SC=52%				
SC=55%	3308524	10828	833	1534
SC=60%				

Not recycled waste has to be treated in MBT . The greater the level of separate collection, the lower the emissions of the treatment because of lower flows treated. By adopting the sieve separation efficiencies in Table 15, the organic and the dry not recycled flows to be address to secondary treatments are calculated (Table 20).

Table 20- Optimization result: organic and dry not recycled waste flows [ton/y]

	Organic not recycled [ton/y]	**Dry not recycled [ton/y]**
SC=50%	35614	53362
SC=52%	34464	50979
SC=55%	32152	47990
SC=60%	29984	41324

The flameless combustion and the landfill are the mutually exclusive secondary treatments envisaged for the organic not recycled fraction (equation 46). Downstream the bio-stabilization treatment, the model suggests the adoption of the flameless combustion and not the landfill in all scenarios analysed. Nevertheless, the flameless technology provides environmental savings only in the 60 % SC scenario. In fact, in case of high levels of separate collection, the dry waste fraction with high fossil origin carbon content decreases being retained upstream in the separate collection network (e.g. plastics, textile, wood etc.). Consistently, the mass flow feeding the flameless unit mainly consists of carbon neutral flow and environmental savings in terms of CO_{2eq} emissions can be obtained.

The high capture efficiency of CO_2 greatly contributes to make this option more environmental compliant. The flameless technology is a promising option to waste diversion.

The dry not recycled fraction feeds the ReMat plant (equation 39). Fractions recovered in this plant are set in the model to the minimum level required by regional guidelines (20% in this case study). Technical reasons suggest only the recovery of paper, cardboard, plastics, ferrous and aluminium cans. In Table 21, the flows of recovered materials are listed and the corresponding total avoided emissions are reported in Table 17. As one can see, separate material flows from unrecycled input stream decrease with the SC level. The only stationary flow is observed for the cardboard stream, which is generated by non-domestic users at a constant rate.

Table 21- Optimization results: recovered waste flows [ton/y]

Waste flows [ton/y]	**SC=50%**	**SC=52%**	**SC=55%**	**SC=60%**
Paper	5009	4528	3959	2555
Cardboard	779	779	779	779
Plastics	6122	5534	4839	3123
Ferrous and Al.cans	1361	1230	1076	694

Gasification and refuse derived fuel production and combustion are mutually exclusive secondary treatments envisaged for the dry not recycled waste (equation 49).

The model reveals RDF as the best environmental solution to whom resort. RDF direct emissions show a downward trend with the SC-L. Such a trend is due to jointly emissions reduction both in production and combustion. The former reduction is due to the decreasing of dry not recycled input flow. The reduction in combustion emissions, which represents the main contribution to RDF emissions, is due to the lower fossil carbon content in the input stream to RDF unit at the higher SC-L. Consistently, the avoided emissions have a downward trend with the level of separate collection. Landfill emissions increases with the level of separate collection pursued (Table 17) due to higher dry scraps from sorting and selection treatment plants. However, a lower both scrap rate and landfill input stream are to be expected in case of higher SC-L; consistently, the expected landfill emissions calculated by the model have to be considered an overestimate of the actual figure.

4.6 Marginal Environmental Benefit index: assessment citizens participation

The MIWMS environmental effectiveness depends on technical and organizational choices as well as on citizens' participation.

A deepen analysis is carried out to investigate results sensitivity on citizens' behaviors. Both the behavior and the involvement of citizens are modeled by means of collection efficiency' parameter. Indeed, the collection efficiency represents the attitude and responsibility of citizens in leaving separate household waste. The higher the involvement of citizens and the level of monitoring, the higher the efficiency value. The collection efficiencies differ greatly with the collection system. Collection systems with low ratio users per containers (i.e. door to door or aggregate collection systems) are characterized by high efficiencies values allowing higher tight monitoring. The Marginal Environment Benefit (MEB) index is defined as follow (49):

$$MEB = \frac{\Delta(Emissions)}{\Delta(Waste\ Sep.Collected)} \qquad \left[{}^{t_{CO_{2eq}}}/_{t}\right] \qquad (49)$$

where the numerator represents the variation of GHGs emissions due to citizens' increased environmental consciousness. The same line of reasoning relates the denominator that represents the variation in the amount of waste separated collected. The MEB index stands for the incremental environmental benefit connected to each separate collected waste ton caused by a moderate (in line with the '*marginal*' concept) increase of collection efficiencies. The MEB index is evaluated by considering a stepwise increase in efficiency of $\Delta\eta = 0.05$ for each waste fraction and collection system.

4.6.1 Scenario analysis

The analysis of how citizens' behaviour affects the GHGs emissions of MIWMS is carried out by varying one by one collection system efficiencies. The minimum and the maximum increase are respectively $\Delta\eta=0,05$ and $\Delta\eta=0,20$ with a steady increase equal to 0,05. To better focuses on the effect of citizens' participation in separate collection, the collection system of the optimized solution is unchanged. Results are provided in Figure 16-17.

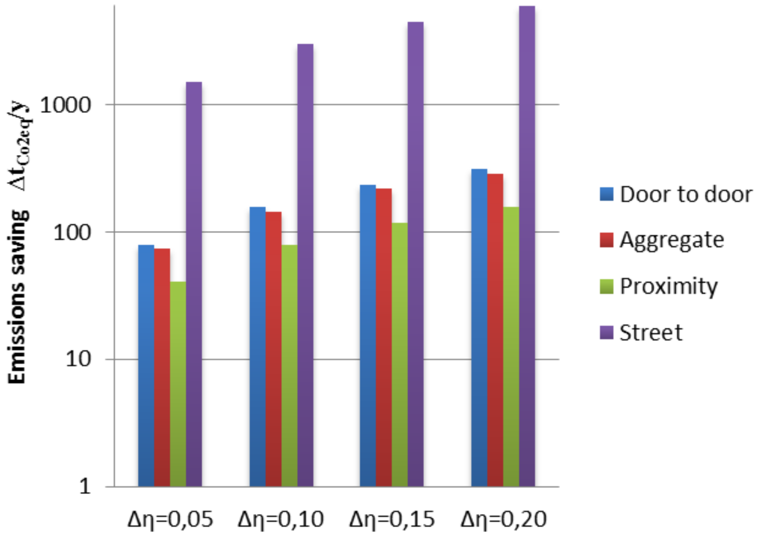


Figure 16- Collection Efficiencies effects on emissions

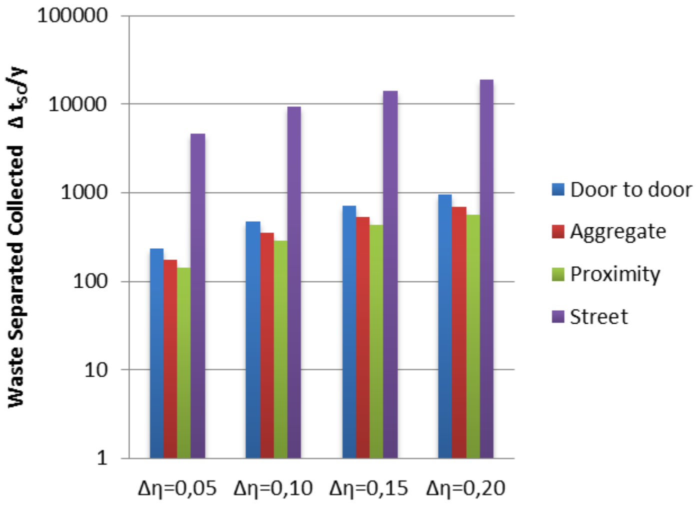


Figure 17- Collection Efficiencies effects on level of separated collection

The vertical axes represent respectively the net emission and the collected flows difference between the scenario with the 'improved' efficiencies and the base scenario with 'standard' efficiencies values. The values are expressed in logarithmic scale to a better results presentation since an huge difference exists between street values and the other collection systems values. For the different collection systems, both the net emissions and the collected flows trends are almost equal but the values differ considerably. It is worth noting that the analysis results are strongly affected by the initial collection solution. The scenario analysis id carried out at a level of separated collection equal to 50%. The greatest environmental saving and flow increase are obtained in the case of street collection for each $\Delta\eta$ tested. The street collection system is the most widespread in the optimal solution. This greatly influences the waste flow collected and in turn the GHGs emissions. The additional savings in emissions is not simply attributable to the increase in dry materials flows recovered and to the incraese in biogas production by recycled organic. When the level of separated collection grows, fewer dry materials (paper, cardboard, plastics)are addressed to RDF production. It means a loss of avoided emissions related to energy production from RDF.

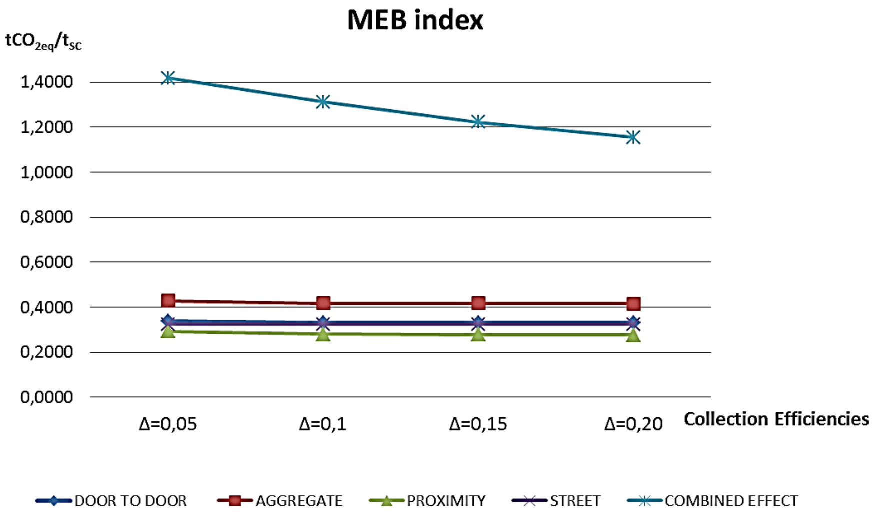


Figure 18- Marginal Environmental Benefit Index

In Figure 18, the MEB trend is shown for each collection system. MEB represent the environmental benefit related to the additional ton of waste collected ascribable to the improvement in social participation.

4.7 Final remarks

Results obtained witness the capability of the model in support decision maker in jointly considering strategic and operational problems of a MSWIMS. The optimal environmental configuration of MWIMSs is not *'unique'* since it depends on both the application context and on separate collection goals. Model solutions stress out the MSWIMSs 'resilience' in terms of both collection systems and treatment plant solutions proposed, flows managed and GHGs savings obtained up with different level of separate collection. A mutual influence exists between the operative planning of the collection service and the strategic planning of waste treatments and valorization. One of the major finding is that to achieve high SC-L is not necessary the recourse to Dtd-CS eventhought characthrized by the highest collection efficiencies. Consistently, the dry recycled collection service is addressed to systems with intermediate collection efficiencies (proximity CS for glass and aggregate CS for dry recycled fractions) which represent the trade-off between the number of collection routes and emission factors of transport means. The recourse to a Multi-material Grouping System ensures high level of SC and at the same time, the drastic collection emissions reduction (as it can be noted in the last scenario SC-L = 60 %). Overall direct and avoided system emissions decrease with the increase of the SC level: however, the latter prevail offering an overall environmental benefit. The recovered dry recycled fractions allow the greater contribution in terms of avoided emissions. It is followed by the WtE processes. Avoided emissions from both materials recovery originated both by separate collection (recycled flow) and from downstream ReMat plants (un-recycled flow) are almost constant in all scenarios. The model increasingly prioritizes the material recovery from dry-recycled fraction. It is evident also considering the percentage of the organic fraction separated collected and consequently treated and valorized in the different scenarios. Biogas production and its valorization is almost constant with the SC-L. On the contrary, contribution to direct and avoided emissions due to RDF production greatly vary with the SC-L. Material vs. energy recovery should be evaluated under market perspectives which suffer from both raw material demand valorization and electric energy price and incentives. The model stands as a decision supports tool where environmental benefit are pursued. Certainty, planning choices at municipal level are taken considering costs too. The minimization of the economic objective can be guaranteed unless the environmental goal can be realized. Coherently, economic concerns should be addressed in the future studies. The analysis carried out shows that great potential to further improvements exist without changes in organizational or technical choices. With the same collection system, which also means the same costs of the collection service, both the net emissions and the level of separated collection achieved can be greatly improved by acting on the awareness of the individual. It therefore appears that awareness programs as well as increasing levels of monitoring are the perfect enhancement of the technical and organizational aspects to maximize the performance of the MWIMS.

CHAPTER 5

WASTE MANAGEMENT PERFORMANCE PREDICTION: AN ANN-BASED DECISION SUPPORT TOOL

5.1 Introduction

This Chapter addresses RQ6 and pursues RO5.

While covering a literature gap (see Chapter 1 and 4), the optimization model just explored in leaves unfilled another opportunity. Indeed, it has been designed for a 'technical' stakeholder. Environmental evaluation complexity of waste management system limits the adoption of analytical tools by a not technical users or a policy maker. Different kind of stakeholders means different analyses purposes and, in turns, different output required as well as input data aggregation. Consistently, an Artificial Neural Network (ANN)-based decision support tool for the prediction of the optimized sustainable performance of an integrated waste management system has been developed. It stands as a user-friendly dashboard designed for a local-policy maker who seeks to have easy insights into potential effects of different waste management policy mainly on greenhouse gases (GHGs) emissions and monetary savings. To ensure technical robustness, the ANN is trained by data set resulting from the optimization model.

In the Section 5.2, both the general framing of ANN methodology and its developed are proposed. Results obtained and insights into model validation are shown in Section 5.3. Final remarks are presented in Section 5.4.

5.2 Materials and Method

Input information of the optimization model requires a considerable technicality and knowledge of the sector. Otherwise, information held by a policy maker has a different nature and a more aggregate form. The same line of reasoning is applied to output information. The ANN simulation model is developed in order to both recognize and assess relationship between the general characteristics of the city, easily accessible, and technical/economic/ environmental performance matter of concern of a policy maker.

5.2.1 Artificial Neural Network: main features

This learning technique mimics the biological learning process occurring in the brain, the neural networks present a robust way to predict actual-value after learning from a supplied sample set. Such a biological system works receiving and processing information to evaluate a series of micro signals, and finally, issuing a response signal consistent with the received information. Similarly, an artificial system transcribes information that will then be decoded by a number of input units (input nodes), processing them by multiple hidden units (hidden nodes), and finally returns, through one or more output nodes, a series of micro signals, which together form the output information. The artificial neuron, also known as the processing element (PE), constitutes the elemental computational unit of a neural network; each node processes the received signals and transmits the result to subsequent nodes.

The ANN is characterized by an inherent ability to learn and recognize highly the nonlinear relationships and then organize dispersed data into a nonlinear model (Xiao et al., 2009).

The input-output relationship is not programmed but is obtained through a learning process based on empirical data. It can be:

- Supervised learning suitable when are available sets data consisting of pairs of input-output data. The transfer function is based on back propagation algorithm. To minimize the prediction error, it progressively corrects the transfer function through a feedback mechanism.
- Unsupervised learning suitable when only inputs data are available. These algorithms attempt to group input data and thus identifying appropriate clusters by using topological or probabilistic methods
- Reinforcement Learning suitable when the aim is only to identify a 'modus operandi' in the reference context. This class of problems poses an agent who explores an environment in which he takes actions. The environment itself provides an incentive or disincentive to the made action.

The serviced learning algorithms are the most used ones.

A transfer function of an artificial neural network transforms an input vector into an output vector based on a matrix of parameters called "weights". The latters are obtained in turn by iteratively applying an error propagation algorithm based on quantification of the difference between "expected value" and "real value". The weight matrix is subsequently validated through further data, not used during the learning phase. Further detail (Facchini et al., 2013).

$$f(\mathrm{B}f(\mathrm{Ax})) \qquad (50)$$

The equation (50) represents the transformation of the input vector into the output vector, according to the neural network function f and the matrices of the coefficients A and B; respectively, of the weights of the function.

Posed wih_{ij} the weight connecting the node i of the input layer with the node j of the hidden layer and, likewise, whoij connecting the hidden layers to the output, the function can be expressed in the form:

$$\mathrm{yo} = f\left(\sum_{j}\left(f\left(\sum_{i}\mathrm{wih}_{ij}\cdot \mathrm{x}_{i}\right)\cdot \mathrm{who}_{ij}\right)\right) \quad (51)$$

From a statistical point of view, the learning process is an iterative process that looks for the solution of a nonlinear multiple regression model, minimizing the error.

5.2.2 Development of ANN-based decision support tool

Different ANNs are adopted, they are used for identify the following targets:

- Waste collection arrangements;
- Quantity of waste separated collected and resulting mixed waste;
- Net yearly emissions due to both direct contribution (collection, treatments and valorisation) and avoided emissions (materials and energy recovery);
- Economic evaluation due to monetary valorisation of waste separated collected in consortium and as well as of energy produced by resulting mixed waste.

Table 22- List of outputs parameters for each ANN

Target	**ANN ID**	**Output**
Waste collection arrangements	#1	Collection typology (C_t): door-to-door, aggregate, proximity and street collection system
Quantity of waste in separate collections and mixed waste	#2	Bio-waste (B_w) [kg/year]
	#3	Paper (Pa_w) [kg/year]
	#4	Plastic (PL_w) [kg/year]
	#5	Glass (G_w) [kg/year]
	#6	Mixed waste (Mix_w) [kg/year]
Net Yearly emission	#7	Emission avoided (E_a) [tCO2eq/year]
Economic evaluation	#8	Separated Collection Income (CI) [k€/year]

For each ANN is identified a set of different output parameters (Table 22) on the bases of four input variables:

- District typology: residential, urban center and old town;
- Population density: low, medium and high;
- Number of citizens;
- Percentage level of separate collections it needs to be ensured.

Data for the ANN training stemming from the optimization model described in the previous chapter. For what concern the economic the evaluation, it is conducted to determine the revenue for the municipalities resulting from an efficient integrated waste management system. The fees ensured by the waste consortia have been considered paper, plastics, aluminium cans and glass (CONAI, 2014). The energy price per kilowatt-hour for the electricity produced.

Two main phases are identified for the design of the prediction model ANN-based, the first phase consisting of data splitting and the second phase consisting of design of the ANN architecture followed by the identification of the best learning algorithm.

The modelling code is developed by Alyuda NeuroIntelligenceTM.

5.2.2.1 Data splitting

The appropriate data splitting can be handled as a statistical sampling problem. Therefore, various classical sampling techniques can be adopted in order to split the data in three subset for training, validation and testing of ANN, most commons are: Simple random sampling (SRS), Trial-and-error methods, Systematic sampling, and Convenience sampling. In this case, Trial-and-error method is adopted, the splitting strategy try to overcome the high variance of the SRS by repeating the random sampling several times in order to minimize the Mean Square Error (MSE) of the ANN. This technique is high time-consuming and requires significant computational costs. For this analysis the data splitting phase is developed on Core i7-4510U with 8GB RAM.

On the basis of best MSE identified, a subset as big as 60% of the available experimental data, which was composed by 72 inputs/output pairs, is used for the ANN training. In this phase, the synaptic weights, which are the links between neurons, have a synaptic weight attached. They are updated repeatedly in order to reduce the error between the experimental outputs and the associated forecasts.

A subset of 20% of the sample was adopted for validation. In particular the adoption of validation sets allows to identifying the underlying trend of the training data subset, avoiding the overfitting phenomenon. As far as concern the testing phase, a sample of 20% is used for testing the forecast reliability of the ANN in the learning phase.

In order to deal with the overfitting problem, the training phase is stopped when the mean square error (MSE) assumed values lower than 0.01. In most cases are required about 20.000 iterations.

5.2.2.2 ANN Architecture

The design of the ANN architecture consists in identifying the number of hidden layers and the number of neurons for each layer. On one hand, many neurons can lead to memorize the training sets with lost of the ANN's capability to generalise. On the other hand, a lack of neurons can inhibit the appropriate pattern classification. In this work, different networks are tested varying the number of hidden layers and the number of neurons in the hidden layer. For each architecture, the software provide to compute a "fitness bar" based on the inverse of the mean absolute error (MAE) on the testing set.

In every cases the best accuracy is achieved adopting ANNs characterized by architecture with only one hidden layers. The numbers of input nodes (N), hidden (K), and output (M) nodes for every network, are given in Table 23.

Table 23-Learning algorithm and architecture adopted for each ANN

ANN	Architecture (N-K-M)	Learning Algorithm
#1	4-2-1	Quick Propagation
#2	4-18-1	Quick Propagation
#3	4-14-1	Quick Propagation
#4	4-11-1	Quick Propagation
#5	4-28-1	Conjugate Gradient Descent
#6	4-17-1	Quick Propagation
#7	4-11-1	Quick Propagation
#8	4-18-1	Quick Propagation

Two different training algorithms namely Quick Propagation (QP) and Conjugate Gradient descent (CG) are adopted. QP is a heuristic modification of the standard back propagation, the output of the m-th output node for the p-th input pattern is given by o_pm (eq.52).

$$o_{pm} = f\left(\sum_{k=1}^{K} \overline{\omega}_{km} o_{pk}\right) \qquad (52)$$

Where f is the activation sigmoidal function (eq. 52), ω ̅_km is the weight between the m-th output neuron and the k-th hidden neuron. The value of o_pk depends by two parameters: the first is given by the weight between k-th hidden neuron and the n-th input neuron (ω ̅_nk). The second parameter is x_pn given by p-th input pattern of n-th neuron.

$$f(x) = \frac{1}{(1 + e^{-x})} \qquad (53)$$

All network weights are updated after presenting each pattern from the learning data set.

The CG learning algorithm starts with a random weight vector that is iteratively updated according the direction of the greatest rate of decrease of the error evaluated as ω^((τ)) in equation 54.

$$\Delta\omega^{(\tau)} = -\eta \nabla E_{\omega(\tau)} \qquad (54)$$

Where E is the error function evaluated at ω^((τ)) and η is the arbitrary learning rate parameter. For each step (τ) the gradient is re-evaluated in order to reduce E.

The performance of the gradient descent algorithm is very sensitive to the proper setting of the learning rate, in case η is too high the algorithm can oscillate and become unstable, for η too small the algorithm takes too long to converge. In this case an adaptive learning rate allows to keep the learning step size as large as possible, ensuring, in this way, the learning rate stable.

5.3 Results and model validation

The parameters predicted by the model are compared to the actual outputs (Figure 19-20-21-22). In order to evaluate the reliability of the model the Mean Absolute Percentage Error (MEPA) and p-values are computed for each ANN.

It is very interesting noted that for all cases the MAPE values are less than 10% and the p-values are very low (Table 24). In other words the reliability of the ANN simulation model is very high.

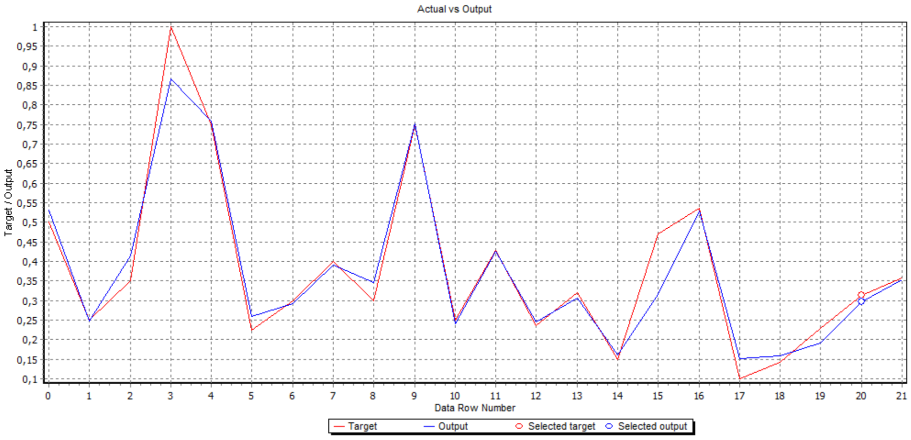


Figure 19- Actual vs. forecast in case of B_w value prediction

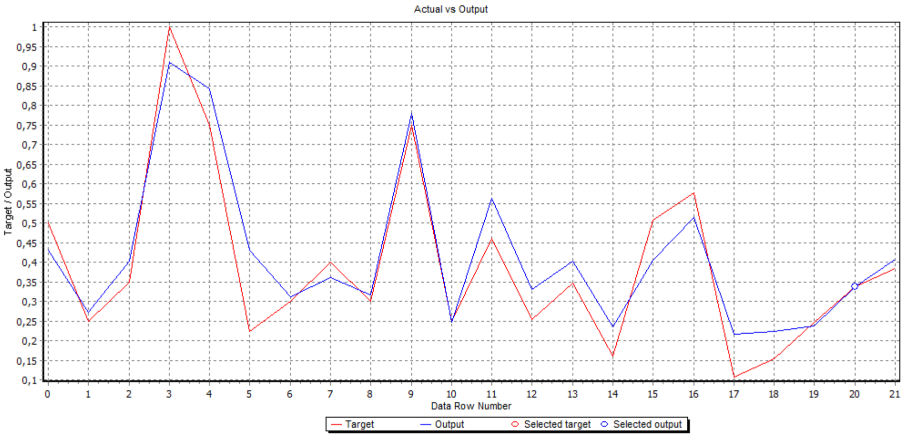


Figure 20- Actual vs. forecast in case of Pl_w value prediction

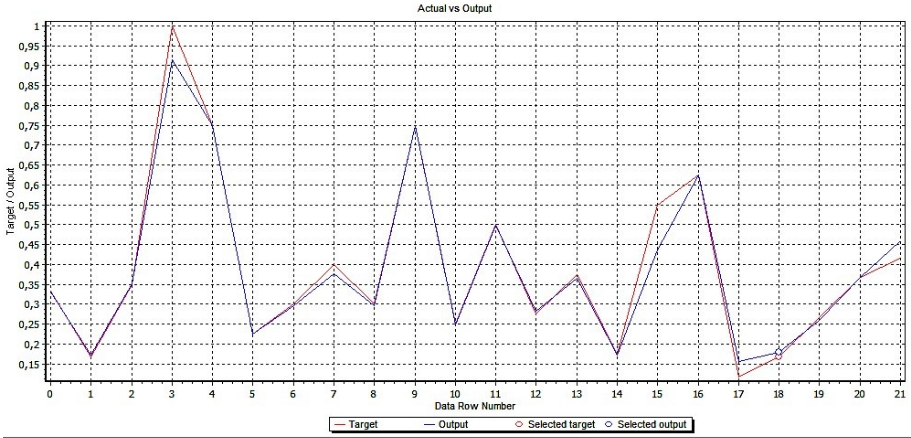


Figure 21- Actual vs. forecast in case of G_w value prediction

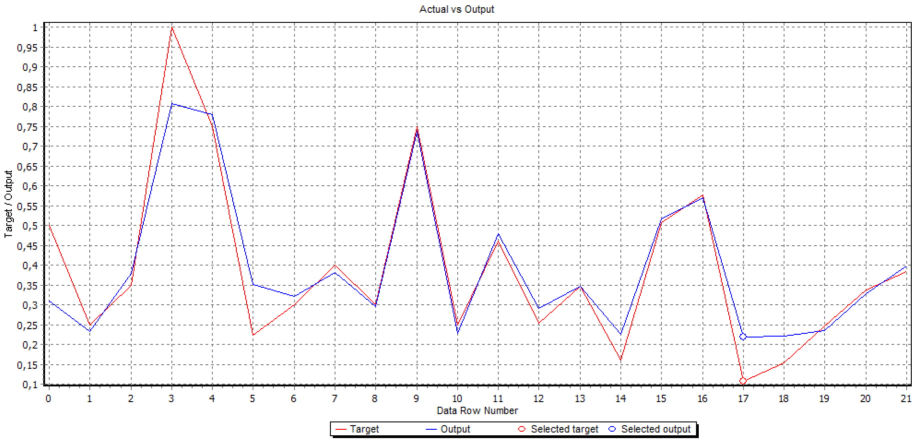


Figure 22- Actual vs. forecast in case of Pa_w value prediction

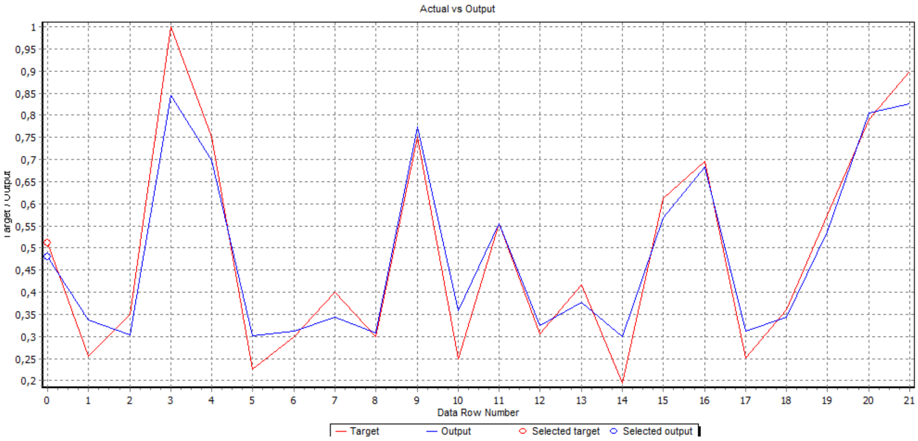


Figure 23- Actual vs. forecast in case of Mix_w value prediction

As far as concern the output provided by ANNs #7 and #8 are identified as 'categorical' and not 'numerical' output (see Table 23). In these cases the high variability of the actual values not allowed to obtain a good estimation of the predicted parameters. Therefore five different levels of cost due to waste collection strategies adopted and to the amount of emission avoided are defined (Table 25).

Table 24- MAPE and p-value for each output provided by ANN simulation

Output	Categorical/ Numerical	MAPE [%]	p-value
C_t	Categorical	4.55	-
B_w	Numeric	3.43	2.74E-20
Pa_w	Numeric	6.59	4.72E-15
Pl_w	Numeric	8.24	1.55E-12
G_w	Numeric	5.52	7.03E-18
Mix_w	Numeric	3.70	6.39E-21
E_a	Categorical	9.09	-
CI	Categorical	9.09	-

The forecast values are in excellent agreement with the actual ones, showing that the developed model is very accurate and has a greater aptitude for evaluating the environmental and economic performance of waste management systems. In order to predict the amount of the E_a and C the increase of the data set used for the training of the ANN is required. Furthermore the inclusion of the new experimental dates allows to enhance the reliability of the forecast and would improve the control of the overfitting phenomenon in phase of the ANN training.

Table 25- Range for each category in case of E_a and C parameters

Output	Level	Range parameters
E_a [tCO2eq/year]	A	$E_a \leq 1000$
	B	$1000 < E_a \leq 2000$
	C	$2000 < E_a \leq 3000$
	D	$3000 < E_a \leq 4000$

	E	$4000 < E_a \leq 5000$
	F	$E_a > 5000$
C [k€/year]	Very cheap	$C \leq 300$
	Cheap	$300 < C \leq 500$
	Medium	$500 < C \leq 700$
	Expensive	$C > 700$

5.4 Final remarks

The complexity and relative difficulty to plan waste management systems and consequently to evaluate economic and environmental performance, is satisfactory solved by adopting an ANN. Thus, the ANN, accurately trained by an analytical optimization model, allows to gather relationships existing among the key features of waste management system, determining the sustainable performance usually matter of concern of a not technical users or a policy maker. Indeed, starting from both demographic and urban fabric features, the tool predicts the most suitable collection configuration, the flows managed as well as the amount of CO_{2eq} emitted/avoided and relative financial flows. Consistently, the developed ANN stands as a user-friendly dashboard designed for a local-policy maker who seeks to have insights into potential effects of different waste management policy mainly on GHGs and monetary savings. Results show the ANN effectiveness in the prediction of the waste flows separated, collected, the GHGs emissions avoided as well as the economic income. The reliability of the model is assessed through the Mean Absolute Percentage Error and p-values. While the MAPE values are less than 10%, the p-values are very low showing that the forecast values are in excellent agreement with the actual ones.

The strengthens of the tool proposed also relies in:

- Continuous improvements since a very high number of real data can be used for the reliability of target prediction
- Easier extensibility to different contexts of application compared to analytical model
- Understanding of relationship between investment in the pivotal social participation and the potential environmental and economic benefits.

Finally, this work suggests that the full integration of analysis, prediction and controlling with a continuous learning in that user-friendly tool esteeming both economic and environmental results is promising. Further improvements will be oriented towards the inclusions in the above mentioned tools of waste management costs for both collection and treatments and the challenging assessment of the sustainable social dimension.

CHAPTER 6

SMART WASTE MANAGEMENT SYSTEMS MONITORING: A WEB-APP FOR IMPLEMENTING A 'CARBON FOOTPRINT CALCULATOR'

6.1 Introduction

This Chapter addresses RQ6 and pursues RO7.

As highlighted in Chapter 1, a literature gap exists. So far, the tools developed are not *'smart-oriented'*. They are not at all conceived as means of communication and information of the different actors involved in such a system. In addition, they are quite 'static' especially in the collection phase although it is recognized as having a key role in reducing emissions. Consistently, in the frame of the European project "RES NOVAE", a web-app named "Smart Waste - Carbon Footprint Calculator (SW-CFC)" is developed. The web-app represents an innovative smart solution to monitor and to evaluate the carbon footprint resulting from the collection of municipal solid waste. Due to the aim to involve all the different actors and stakeholders, the web-app is designed with two different users profile: public decision makers and citizens. The public decision-makers can use the app to assess the carbon footprint of the 'status quo' systems and to evaluate the impact of potential changes in different technical and organizational choices for the waste collection in terms on both emissions and level of separated collection achieved. On the other hand, the use of SW-CFC can stimulate citizens' consciousness leading their actions on right collection practice.

Firstly, the context in which the study is carried out is presented in Section 6.2. The web-app, its interfaces as well as calculation algorithms applied are presented in Section 6.3. Final remarks are discussed in Section 6.4.

6.2 Background

Rethinking the urban spaces focusing on citizens' need, streamlining resources and making more efficient services and utilities play a key role in the achievement of a city' sustainable development. Consistently, the theme of the 'Smart City' is the centre of an intense debate. According to the definition of (Batty et al., 2012): "*Cities are becoming smart not only in the way we can automate routine functions serving individual persons, buildings, traffic systems but in ways that enable us to monitor, understand, analyse and plan the city to improve the efficiency, equity and quality of life for its citizens in real time*". Indeed, Smart City development implies continuous innovations not only supplying 'smart objects or smart services' but also ensuring closer involvement of citizens in governance processes and closer monitoring of needs and services (CDP, 2013).

"Smartness" in city, services, decision-making process and citizens is the milestones in the European Project "RES NOVAE". The project aims at increasing energy efficiency, reducing greenhouse gas emissions, providing new value added services to various stakeholders and overall improvement in quality of life. The 'smart governance' is a key driver since it means stakeholders cooperating in decision-making processes and public or social service. In this perspective an Urban Control Centre

(UCC) has been designed. The UCC provides energy and environmental information to the public administration, citizens and other interested players. The project represents the first pieces of the puzzle aimed at creating a sustainable urban environment in Bari.

Among the different urban action areas, the waste management systems deserve considerable attention.

In that context, the web-app "Smart Waste - Carbon Footprint Calculator" is developed.

6.3 Materials and methods of the Carbon Footprint Calculator

The carbon footprint is an index that measures the total greenhouse gas emissions caused directly and indirectly by a person, an organization, an event or a product and it is expressed in terms of CO_{2eq}.

Variables object of the service planning by a local decision makers have been identified to evaluate the carbon footprint of the municipal waste collection system. Parameters affected by peculiarities of the application area or of the collection service have to be considered too. It is referred to area' urban fabric constraints or to regulatory and technical constraints.

An overview of the variables and relative influences on the carbon footprint are shown in Figure 24. Basically, emissions depend on the distance travelled to ensure the collection service demand in a defined timeline. Consistently, a '*distance-based approach*' (IPCC, 2006) for estimating CO_{2eq} emissions for each type of vehicle, payload and average speed is used. Going further into details, the total distance travelled to fulfill collection service demand depends on the frequency of collection as well as on the number of work-shifts for each collection route and on the average distance covered in each collection route. The number of work-shifts depends on the productivity of the collection work-team employed that is in turn influenced by the waste fraction collected and by both collection grouping and system adopted.

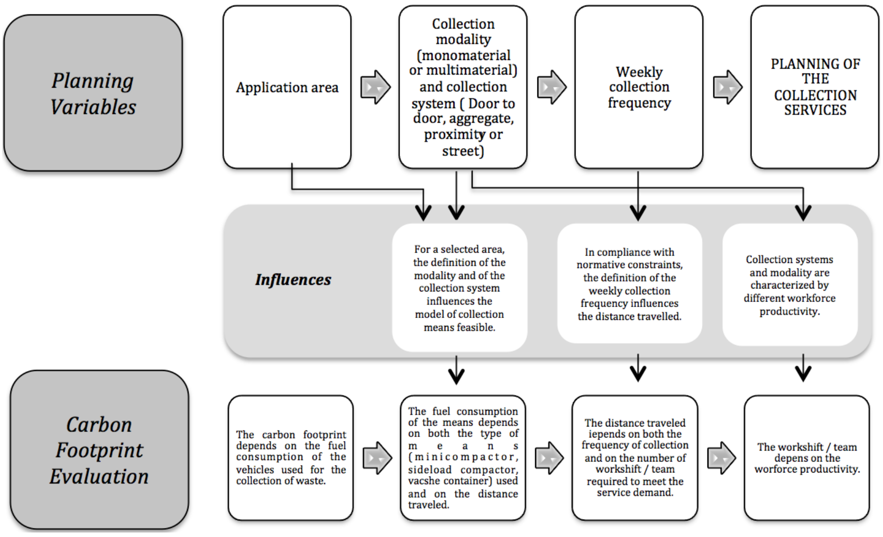


Figure 24- Influences on the assessment of the Carbon Footprint.

Instead, the average distance travelled depends on the type of mean employed. For each waste fraction, emissions are calculated as in (55).

$$CF_{collection} = EF \cdot W \cdot \bar{d} \cdot f \quad (55)$$

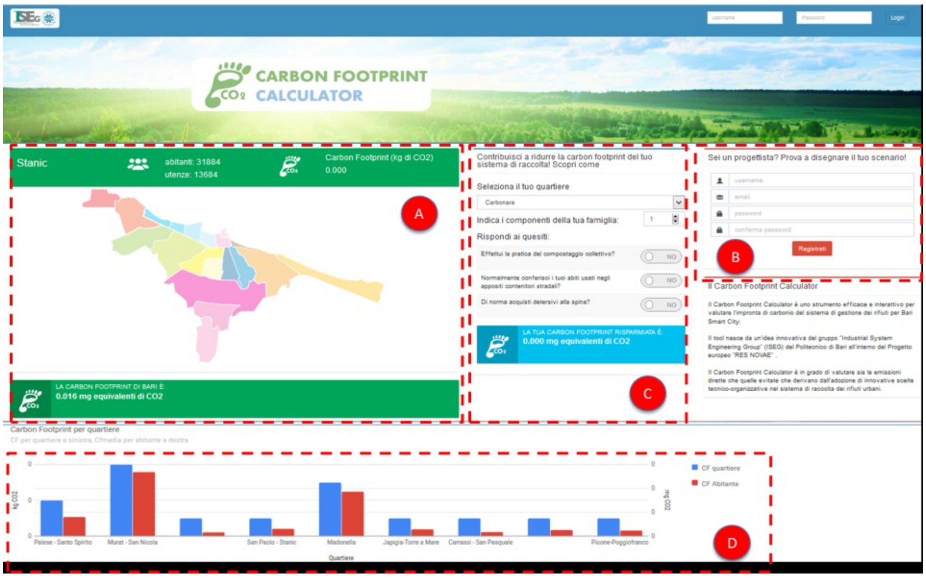
where:

- $CF_{collection}$= Carbon Footprint for waste collection in a set timeline [t_{CO2eq}/ timeline];
- EF = emission factor of the collection mean [t_{CO2eq}/ km];
- W= number of work-shift for each collection routes [work-shift/ collection route];
- $\bar{d}$ = average distance travelled in a work-shift [km/work-shift];
- f = collection frequency [collection route/timeline].

Readers can refer Chapter 3-4 for collection systems and grouping systems features such as collection efficiencies, workforce productivity, and means characteristics (payload, average distance). Emissions factor adopted in the tool for mini-compactor and side/rear load compactor are provided by (Inemar, 2013).

6.4 Web-app “Smart Waste - Carbon Footprint Calculator”

Hereinafter, a detailed description of the app is provided exploiting actual screens of the tool. The app will be available for free to the users at the following link: http://resnovae.peachwire.com. As aforementioned, the app is build up in the frame of the European project ‘RES NOVAE’ for Bari Smart City. The tool operates at municipal level with a deeply insight at city's district level. Nevertheless it can be easily scaled up to other city or to regional level. The app’ home page is shown in Figure 25. As it can be seen, Section B of Figure 25 relates the expert user profile while the Section C of Figure 25 relates the citizen user profile. The two user profiles have been developed with different functions and purposes, but with the common goal to monitor the environmental impact and to raise awareness on sustainable development.



Stanic

abitanti: 31884
utenze: 13684

Carbon Footprint (kg di CO2)
0.000

LA CARBON FOOTPRINT DI BARI È:
0.016 mg equivalenti di CO2

Contribuisci a ridurre la carbon footprint del tuo sistema di raccolta! Scopri come

Seleziona il tuo quartiere: Carbonara

Indica i componenti della tua famiglia: 1

Rispondi ai quesiti:

Effettui la pratica del compostaggio collettivo? NO

Normalmente conferisci i tuoi abiti usati negli appositi contenitori stradali? NO

Di norma acquisti detersivi alla spina? NO

LA TUA CARBON FOOTPRINT RISPARMIATA È:
0.000 mg equivalenti di CO2

Sei un progettista? Prova a disegnare il tuo scenario!

username
email
password
conferma password

Il Carbon Footprint Calculator

Il Carbon Footprint Calculator è uno strumento efficace e interattivo per valutare l'impronta di carbonio del sistema di gestione dei rifiuti per Bari Smart City.

Il tool nasce da un'idea innovativa del gruppo "Industrial System Engineering Group" (ISEG) del Politecnico di Bari all'interno del Progetto europeo "RES NOVAE".

Il Carbon Footprint Calculator è in grado di valutare sia le emissioni dirette che quelle evitate che derivano dall'adozione di innovative scelte tecnico-organizzative nel sistema di raccolta dei rifiuti urbani.

Carbon Footprint per quartiere

CF per quartiere a sinistra, Cfmedia per abitante a destra

Figure 25-Home page of ‘Smart Waste - Carbon Footprint Calculator’

The Section A Figure 25 represents the city’ map with details of districts and different areas inside the district (characterized by nuances of the same color). A simple scroll on that map allows showing the annual carbon footprint for the different areas due the current collection service in place. For an easier comparison among the different districts, results in terms of (t_{CO2eq}/inhabitants) both and (t_{CO2eq}/ area) are also shown in a histogram, as evident in the Section D Figure 25.

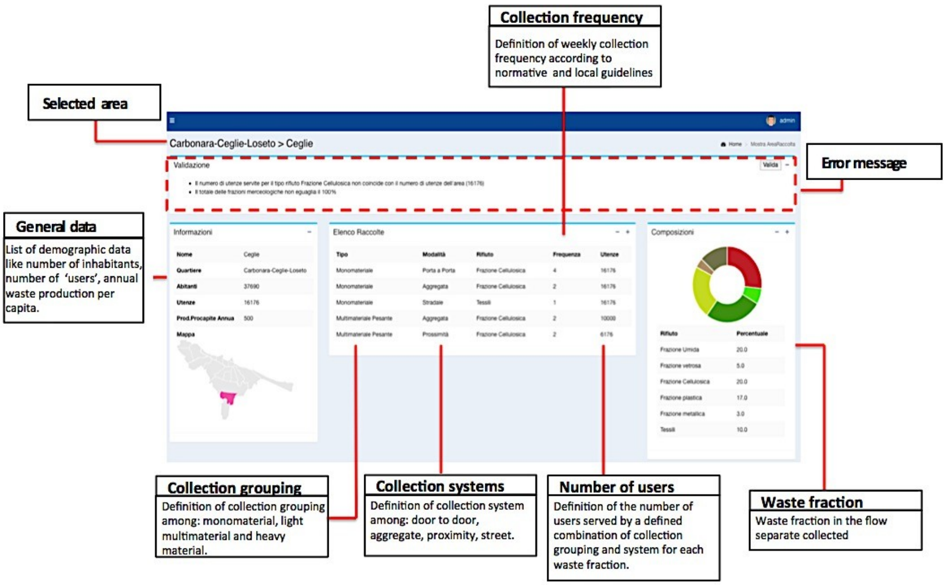
6.4.1 App Interface for public decision makers

The web-app will allow the public decision maker to assess the carbon footprint attributable to both the waste collection system already implemented and, through scenario analysis, that caused by innovative technical and organizational solutions for the recyclable and unrecyclable waste flows collection.

The steps followed by the users are shown below. They relate the characteristic elements to identify the interdependent and/or complementary operating modalities that affect the environmental impact of the collection area.

A user registration mechanism is foreseen before proceeding with the assessments (Figure 25- Section B). The required fields are the username and the email at which the user will receive the automated system-generated password. The decision-making process starts with the definition of the area. The planning collection service interface is shown in Fig.26. For each area, in the top left are listed demographic data like the number of inhabitants and the number of families (defined *'users'* from the point of view of the collection) as well as the annual waste production per capita. The waste fractions considered in the model are the follow: organic, paper and cardboard, plastics, ferrous and aluminum cans, glass, textile, wood and others. Constraints about grouping system to be adopted following rules depicted in section 3.2.1.1. Four types of collection systems are foreseen in the tool: door to door, aggregate, proximity and street. The definition of the weekly collection frequency occurs in compliance with constraints set by normative regulations and guidelines.

To plan the collection service, the public decision maker is required to enter for each waste fraction the number of users served with a defined grouping system and collection system with a particular weekly collection frequency.



Carbonara-Ceglie-Loseto > Ceglie

Validazione

- Il numero di utenze servite per il tipo rifiuto Frazione Cellulosica non coincide con il numero di utenze dell'area (16176)
- Il totale delle frazioni merceologiche non eguaglia il 100%

Informazioni

Nome	Ceglie
Quartiere	Carbonara-Ceglie-Loseto
Abitanti	37690
Utenze	16176
Prod.Procapite Annua	500
Mappa	

Elenco Raccolte

Tipo	Modalità	Rifiuto	Frequenza	Utenze
Monomateriale	Porta a Porta	Frazione Cellulosica	4	16176
Monomateriale	Aggregata	Frazione Cellulosica	2	16176
Monomateriale	Stradale	Tessili	1	16176
Multimateriale Pesante	Aggregata	Frazione Cellulosica	2	10000
Multimateriale Pesante	Prossimità	Frazione Cellulosica	2	6176

Composizioni

Rifiuto	Percentuale
Frazione Umida	20.0
Frazione vetrosa	5.0
Frazione Cellulosica	20.0
Frazione plastica	17.0
Frazione metallica	3.0
Tessili	10.0

Collection frequency
Definition of weekly collection frequency according to normative and local guidelines

Selected area

Error message

General data
List of demographic data like number of inhabitants, number of 'users', annual waste production per capita.

Collection grouping
Definition of collection grouping among: monomaterial, light multimaterial and heavy material.

Collection systems
Definition of collection system among: door to door, aggregate, proximity, street.

Number of users
Definition of the number of users served by a defined combination of collection grouping and system for each waste fraction.

Waste fraction
Waste fraction in the flow separate collected

Figure 26-Web-App: planning collection service interface

In this phase, the planning experience plays a key role. Indeed, city' urban features have a remarkable influence on collection systems. The experience and the awareness of urban fabric restrictions allow for defining a collection service fitting with the characteristics and the needs of the interest area. To help the planning, the maximum number of users employable is added for each collection system. Regard to collection means, the choice of the type of means by the user will be bound to the type of collection system previously adopted. Downstream the definition of the collection service, it is possible to quantify the flows intercepted in the separate collection loop. Indeed it should be pointed out that for every waste fraction, each combination of grouping and collection system is characterized by a specific value of collection efficiency. Therefore, the composition of waste collected is plotted in the pie chart (Fig.26) and the separate collection index is displayed too, as in Figure 27.

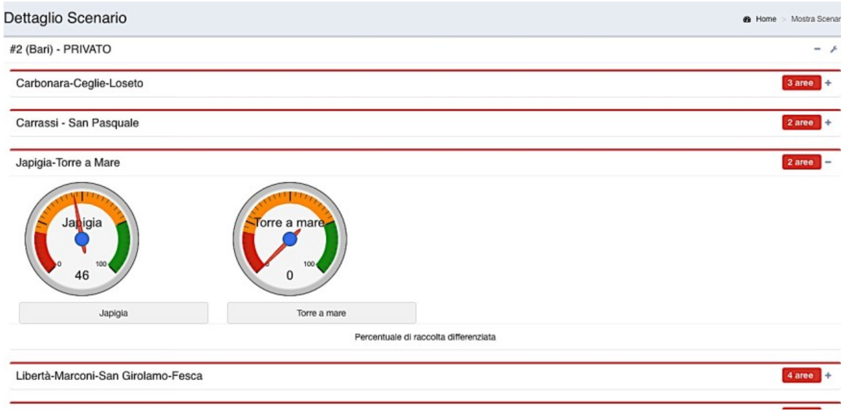


Figure 27- Web-app planning result: separate collection index

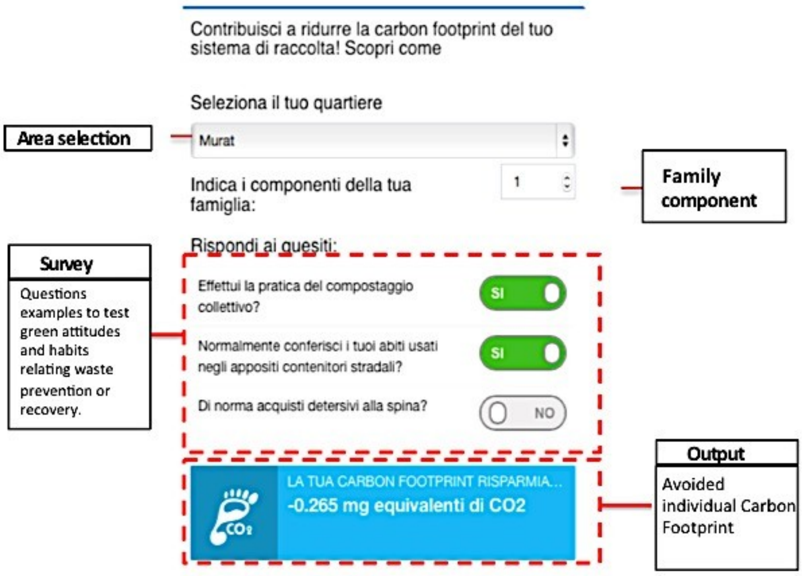
Proper error messages will be displayed to signal failures in fulfillment service demand or failure in the quantification of waste collected. The outcome of the decision-making process will be displayed in terms of annual CO_{2eq} emissions.

6.4.2 App Interface for citizens

For the citizen profile the assessment procedure is simplified. Coherently, the procedure is consistent with the training, information, and increased social participation purposes. Indeed, no registration is required.

Once the user select the area from the home page (Figure 25 section A), the app automatically loads the collection system implemented in the district from a remote database. The results displayed, represents the annual GHGs emissions due to the collection in such area. Calculating the avoided individual carbon footprint due to green attitudes and habits represents the interactive section of the 'citizen menu' (Figure 25-Section C). For the individual carbon footprint evaluation, the user is required to select the home area and to enter the effective number of household member. To increase the awareness of behaviors affecting waste management environmental impact, a short survey is proposed (Figure 28).

Green attitudes and habits investigated are: home composting for the organic fraction, the use of detergents on tap to reuse the plastic bottle and inserting textiles into appropriate receptacle. Results are shown in terms of individual avoided carbon footprint (t_{CO2eq}/inh year). Avoided emissions have a twofold source. The first relates the avoided collection and consistently avoided emissions specific for the selected area. The secondo relates avoided emissions due to the valorization of the specific waste fraction. Increasing citizen participation as well as improving the citizen' awareness of the effects that an individual behavior has on the collective well-being and on the environment, are the main expected benefits.



Contribuisci a ridurre la carbon footprint del tuo sistema di raccolta! Scopri come

Seleziona il tuo quartiere

Murat

Indica i componenti della tua famiglia: 1

Rispondi ai quesiti:

Effettui la pratica del compostaggio collettivo? SI

Normalmente conferisci i tuoi abiti usati negli appositi contenitori stradali? SI

Di norma acquisti detersivi alla spina? NO

LA TUA CARBON FOOTPRINT RISPARMIA...

-0.265 mg equivalenti di CO2

Figure 28- Web-app: Citizens interface

6.5 Final remarks

Starting from KPI of waste production and collection, the 'Smart Waste-Carbon Footprint Calculator' will enable citizens and decision makers to assess the carbon footprint of the integrated system taking into account both the virtuous citizens behaviors and the technical and organizational decisions of policy makers.

Indeed, the public decision maker is able to jointly assess the carbon footprint due to the collection service already implemented and to investigate, through scenario analysis, the effects on the carbon footprint due to innovative technical and organizational collection choices.

On the other hand, the use of SW-CFC can stimulate citizens' consciousness leading their actions on right collection practice. By a short survey section, the app calculates and shows citizen' green attitudes and habits in terms of avoided emissions. The awareness of their impact in terms of emissions will enable individuals to understand the contribution that a virtuous behavior on societal wellbeing.

CONCLUSIONS

To promote the transition towards circular economy, the aim of this thesis has been develop both strategic planning models and analytical ones to evaluate and predict the effects on economic, environmental and social performance due to the implementation of new business pattern and of efficient waste management system. Indeed, these latter have been recognized as key factors in fostering the transition towards CE.

The identification of this goal is widely supported by a jointly analysis of scientific literature and empirical experiences. Consistently with the research objectives identified for each gap recognized in the Chapter 1, the thesis was developed. All the objectives contribute to the attainment of the main one abovementioned. Consistently with the one proposed in the section 1.3, a further schema will be presented with the results achieved for each Research Answer and Research Objective projected in the beginning of that study. The results are described below.

Focusing on implementation of new business model 'circular-oriented', the literature recognized that it is necessary that CE strategies are evaluated in an integrated supply chain approach. However, a shortage of instruments and model was found about it. Consistently, to understand the effects on economic, environmental, social and technical performance due to a shift from a traditional ownership-based business model to a leasing-based business model and closed-loop schemes, a Fuzzy Cognitive Map is developed. Supported by a case study proposed by the Ellen MacArthur Foundation, the washing machines segment is explored. The

FCM allowed the identification of all impacts extensive on all actors and their relationship.

The benefits on the environmental and social sides seem to be clear and well understood: material recovery, remanufacturing and recycling strategies that would decrease waste generation and emissions, while a wider access would be guaranteed to high-end and technologically updated products, increasing also the customer service level and decreasing the size of illegal secondary market. On the economic dimension, some other considerations should be made. Initially, the market is not ripe enough to trigger the virtuous circle itself. Supportive policy measures to ensure the economic viability for companies is needed. Targeted policies to improve user awareness and commitment in CE issues, fostering the adoption of the leasing model and considerably increasing the sales of refurbished products is needed to. Finally, while the cost for customers is expected to decrease, the costs bore by the producer need to be further explored, in order to ensure the economic sustainability for the company and the successful diffusion of the business model. Rebound effects should also be considered when evaluating environmental and economic benefits.

Conceiving waste as a resource, rather than a ‘no-value wreck’ or an environmental problem, is the other side of ‘circular economy coin’.

Literature and practices analyses have highlighted the need to create a decision framework to face the inner complexity of waste integrated management system. Consistently, a decision-making framework is proposed to tackle the multifaceted complexity and ensure transparency and repeatability of decision-making processes. The holistic approach, giving the overall picture of the waste management process, is essential for the strategic and operational planning. To ensure more efficient waste management, different technologies should be explored. Coherently, all viable alternatives have been investigated by moving the boundaries of analysis beyond the technologies currently used. By way of example, multimaterial collection solutions are considered, although practical examples can only be found overseas. The great potential of such a organizational arrangements is still unexplored. The same line of reasoning is applied to other collection arrangements and treatments options. Hereafter the systematization of such knowledge to help in the decision making process, the framework leading up to identifying the variables object of evaluation and r

Considering the contribution on GHGs emissions of inbound logistics activities, a further analysis is carried is to identify the best Material Handling Equipment (MHE). A model to select the best environmental MHE for inbound logistic activities has been developed. Environmental performance of the MHE has been evaluated in terms of carbon Footprint. The model is tested with a tool adopting a VBA macro as well as a simulation software allowing the evaluation of energy and time required by the forklift in each phase of the material handling cycle. Nowadays, it is not possible to identify 'a priori' a particular engine equipped forklift performing better than others under an environmental perspective. Considering average weight of bale handled, such a finding has led in the formulation of the optimization model described hereinafter, to adopt an LPG forklifts in treatment plants handling .

A Mixed Integer Non-linear Programming model to minimize the carbon-footprint of municipal integrated waste management system is developed. It is deemed necessary since both the environmental goals driven planning and relative post-assessment have been for a long time underestimated. The model refers to the general framework, previously described, including both technical and organizational options for all phases of an integrated municipal solid waste system. the model implementation, the targeted-user have insights into potential alternatives and related consequences in terms of GHGs emissions due to decisions in each MWIMS phases of which otherwise he would be unware. Forecasting quantity and related quality of waste flows treated in MWIMS is a very complex task required a systemic approach as the one proposed.

The model optimizes five variables pertaining operative collection service planning (3 variables) and strategic treatment and valorization planning (2 variables). Variables at the operative level relate the grouping system activation (binary variables), the number of users served by each collection system modeled and weekly collection frequency. At the strategic level, the model enables to identify the amount of each waste flows to be addressed to treatments and valorization plants in order to maximize the benefit in terms of avoided emissions. The collection service design affects quantity and quality of waste to be treated and recovered. This in turns affects waste treatment and valorisations to optimize environmental performance of the whole system. Moreover, the potential of a treatment or valorisation process for a specific waste fraction influence the upstream collection moving the latter towards a combination of grouping and collection system with higher efficiency even if responsible of high emissions. A mutual influence between the strategic and the operational level exists. It is difficult to consider all the aspects without an analytical model. The main strength of such a model is to catch all the above mentioned influences and using them in the planning. To test the model effectiveness it has been applied to a full case study relating Bari, a middle size city in Apulia region. Results obtained witness the capability of the model in support decision making. The optimal environmental configuration of MWIMSs is not *'unique'* since it depends on both the application context and on separate collection goals. Different scenarios are explored ranging from a level of 50% to the maximum level of 60%. Consistently, the dry recycled collection service is addressed to systems with intermediate collection efficiencies. The recourse to a Multi-material Grouping System ensures high level of SC and at the same time, is envisaged only for targeted level of separated collection up to 60%. The recovered dry recycled fractions allow the greater contribution in terms of avoided emissions. It is followed by the WtE processes. Avoided emissions from materials recovery originated by separate collection (recycled flow) and downstream ReMat plants (un-recycled flow). Avoided emissions from energy recovery originated both by biogas, RDF valorizations. The model increasingly prioritizes the material recovery from dry-recycled fraction. It is evident also considering the percentage of the organic fraction separated collected and consequently treated and valorized in the different scenarios. Biogas production and its valorization is almost constant with the separated collection level. On the contrary, contribution to direct and avoided emissions due to RDF production greatly vary with the SC level. Material vs. energy recovery should be evaluated under market perspectives which suffer from both raw material demand valorization and electric energy price and incentives.

It is well known that municipal waste integrated management system performance depend not only on operative and strategic technical aspects. The role of citizens participation is investigated too. Both the behavior and the involvement of citizens are modeled by means of collection efficiency' parameter. Indeed, the collection efficiency represents the attitude and responsibility of citizens in leaving separate household waste. The marginal Environmental Benefit is introduced for that purpose. The MEB index stands for the incremental environmental benefit connected to each separate collected waste ton caused by a moderate (in line with the '*marginal*' concept) increase of collection efficiencies. A scenario analysis is conducted. Results show that great potential to further improvements exist without changes in organizational or technical choices. Indeed, with the same collection system, which also means the same costs of the collection service, both the net emissions and the level of separated

collection achieved can be greatly improved by acting on the awareness of the individual. Targeted policy and investments aiming at increase levels of monitoring and citizens awareness are the perfect enhancement of the technical and organizational aspects to maximize the performance.
The targeted user of such a decision support tool is a technical user inclined and tangled up in really technical aspects. This aspects could limit the application of that tool by a different users interested in evaluation on a more general level.

Consistently, an Artificial Neural Network (ANN)-based decision support tool for the prediction of the optimized sustainable performance of an integrated waste management system has been developed. It stands as a user-friendly dashboard designed for a local-policy maker who seeks to have easy insights into potential effects of different waste management policy mainly on greenhouse gases (GHGs) emissions and monetary savings. The ANN is trained by data set resulting from the optimization model. . The robustness of the model is assessed through the Mean Absolute Percentage Error and p-values. The forecast values are in excellent agreement with the actual ones. The use of ANN enables continuous improvements since a very high number of real data can be used for the reliability of target prediction. Furthermore, it allows an easy understanding of relationship between investment in the pivotal social participation and the potential environmental and economic benefits. The encountered limit relates the inclusions of waste management costs for both collection and treatments. It will be matter of concerns in following study.

So far, the tools developed are not *'smart-oriented'*. Furthermore, the role of communication and information as means to increase involvement and awareness of public policy/technical decision makers and citizens is completely unexplored. Consistently, in the frame of the European project “RES NOVAE”, a web-app named “Smart Waste - Carbon Footprint Calculator (SW-CFC)” is developed. The web-app represents an innovative smart solution to monitor and to evaluate the carbon footprint resulting from the collection of municipal solid waste. The test –case is Bari Smart City. The web-app allows:

- public decision-makers to assess the carbon footprint of the ‘status quo’ systems and to evaluate the impact of potential changes in different technical and organizational choices for the waste collection in terms on both emissions and level of separated collection achieved.
- Citizens to understand how much and in which way they contribute to the overall performance. Indeed, by means of an interactive map it is shown the actual collection emissions in his residence area and by means of a ‘green- survey’ it is quantified potential benefit of his ‘green habits or attitudes’. The use of SW-CFC can stimulate citizens’ consciousness leading their actions on right collection practice.

Hereinafter, the conclusive scheme is reported.

The models stand as a decision supports tool where environmental benefit are pursued. Certainty, planning choices at municipal level are taken considering costs too. The minimization of the economic objective can be guaranteed unless the environmental goal can be realized. Coherently, economic concerns should be addressed in the future studies.

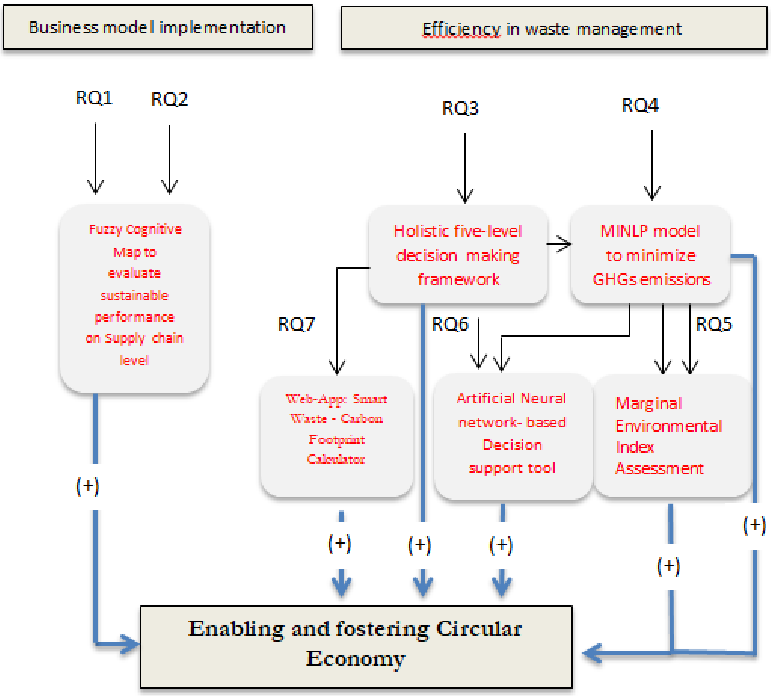


Figure 29- Overview of Research Questions, Research Results and relationship

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APPENDIX I

In the following the full list of commercial users considered in the analysis is shown. Data are provided by the CCIA of Bari. As it is stated in the Chapter4, it is supposed a DtD-collection service for this kind of users.

Table 26- Commercial Users in Bari (CCIA)

Type of non-domestic user	Number [#]	Waste produced		
		Organic	**Cardboard**	**Glass**
Agricolture and Forestry	814	X		
Mining and quarryng	12			
Production acvtivity	2218			
Electricity, gas, steam provision etc.	42			
Sewer, water provision etc.	52			
Construction	2986			
Wholesaler and retailer	11022		X	X
Transport and warehouse	1029			
Catering and accomodation services	1761	X		X
Information and comunication services	935			
Financial and insurance activities	734			
Real estate activities	901			
Scientific and techinical services	1456		X	
Rental, travel agencies, business support services	1021			
Public administration	1			
Education	225		X	
Healthcare	234			X
Artistic and sport activities	434			

Other services	1177
Others	2895

For a conservative assessment, it can be observed that paper and plastics waste flows are not considered for commercial users. It is due both to a duple reason. Firstly, the distinction of the portion of such waste flows attributable to non-domestic users is difficult because there is no reliable data. Secondly, the conferral of that wastes into the domestic collection circuit is frequent.